INDEXED

Volume 9 APRIL, 1939 Number 1

Journal of Sedimentary Petrology

A Publication of the Society of Economic Paleontologists and Mineralogists
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« CONTENTS »

Bacterial Counts in the Muds of Crystal Lake . . . *Philip L. Carpenter* 3

Shoal-Water Deposits of the Bermuda Banks . . . . . *Jean P. Todd* 8

The Occurrence of Spore Coal in the Williamston Basin, Michigan . . . . . *S. G. Bergquist* 14

Igneous and Metamorphic Rocks from Pleistocene Gravels of Central Louisiana . . . . . *H. N. Fisk* 20

Sorting and Transportation of Material in the Swash and Backwash . . . . . *O. F. Evans* 28

Varve-like Deposit in a Solution Channel . . . . . *W. D. Keller* 32

Types and Sources of Sediments Deposited by the South Canadian River in New Mexico and Texas . . . . . *Raymond Sidwell* 36

REVIEWS

Krumbein, W. C., and Pettijohn, F. J., Manual of Sedimentary Petrography . . . . . *Stanley A. Tyler* 42

Tickell, Frederick G., The Examination of Fragmental Rocks . . . . . *R. Dana Russell* 42

Journal of Sedimentary Petrology

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 9, NO. 1, PP. 3–7, TABLES 1–5, APRIL, 1939

BACTERIAL COUNTS IN THE MUDS OF CRYSTAL LAKE—AN OLIGOTROPHIC LAKE OF NORTHERN WISCONSIN[1]

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ABSTRACT

This paper is a report of bacteriological analyses made on bottom deposits of Crystal Lake, an oligotrophic lake in the Northern Wisconsin State Forest. Twenty-nine mud samples representing eight cores were studied. Anaerobic bacteria as well as aerobic and facultative bacteria decreased in numbers at increasing depths in the mud. Bacterial counts are much lower than similar reported counts for bottom deposits of the eutrophic Lake Mendota, in Southern Wisconsin. This is correlated with the lower content of organic and mineral matter in Crystal Lake water.

Several investigators have reported observations on the bacterial flora of the waters and sediments of Wisconsin lakes, particularly of Lake Mendota (Fred, Wilson and Davenport, 1924; Williams and McCoy, 1935). The investigation recorded in this paper was undertaken during August, 1937, in connection with a study of the sediments of Crystal Lake, a soft-water lake in the Northern Wisconsin State Forest. Results of sedimentational studies will be presented by W. A. Broughton and H. D. Becwar of the University of Wisconsin.

Samples for bacteriological and geological study were secured in two ways: (1) sludge representing the sediments of the immediate bottom was taken with an Ekman dredge, and (2) sediments beneath the bottom were secured by means of a sampling device designed by Dr. W. H. Twenhofel. This sampler consists of a three-inch pipe inside which is placed a sheet-metal cylinder. After a sample in the form of a core is secured by driving the sampler into the mud, it may be removed and examined by withdrawing the sheet metal cylinder. For bacterial analysis, samples were always taken from the center of the core after searing the surface with a red-hot spatula. The cores within the six-foot cylinder were rarely over a meter in length, although the sampler was driven into the mud to a depth of approximately 3 meters. Three samples were usually taken for bacteriological study, from the top, middle and bottom of the cores. The sampler was mounted on a raft composed of two boats. Cores were taken at eight stations and in water from 14 to 20 meters deep. In all, 29 sludge and core samples were analyzed.

Moisture determinations were made on each sample,[2] so that plate and dilution counts are reckoned on the dry basis. The water content of the samples ranged as follows:

Water Content of Samples, in Per Cent

Sludge	93–95
Top of core	86–94
Middle of core	62–91
Bottom of core	36–88

Plate counts for aerobic and facultative bacteria were made on a modified sodium caseinate agar (Henrici and McCoy, 1938). Five replicate bottle plates were poured from several dilutions of each sample and incubated ten days at 28–30° C. Only that dilution was counted which showed between 30 and 300 colonies per plate. Chromogenic and mold or actinomyces colonies were

[1] Supported by a grant from the Brittingham Trust Fund, University of Wisconsin.

[2] The author wishes to express his appreciation to Mr. W. A. Broughton for these data.

N Y P L

counted separately. Anaerobic bacteria were estimated by a dilution method by transferring one milliliter portions of several dilutions of the sample into each of five replicate tubes of cornmash and of Bacto-beef. These were observed for one week for gas production and putrefaction. In addition, the following physiological groups of bacteria were detected by single tube inoculations of approximately one-tenth gram of the sample: (1) urea-fermenters, (2) aerobic cellulose-fermenters, (3) anaerobic cellulose-fermenters, (4) denitrifying bacteria, and (5) pectin-fermenters.

RESULTS

A summary of the total number of aerobic and facultative organisms developing on the sodium caseinate agar plates is given in Table 1. Colony characteristics indicated presence in the mud of a wide variety of bacterial species typical of a soil flora. Chromogenic bacteria were prominent, particularly those producing red, orange and yellow pigments. Spreading colonies were frequently observed, and mold and actinomyces colonies were also occasionally noted.

TABLE 1.—*Summary of aerobic and facultative plate counts of samples taken from the mud deposits of Crystal Lake (bacteria per gram of dry mud)*

Core	Sludge	Top	Middle	Bottom
I		750	340	30
II	14,900	7,850	11,200	350
III	6,740	20,600	200,000	54
IV	4,000	190	12,000	200
V	9,600	5,900	185	
VI	3,660	1,400	130	310
VII		430	250	225
VIII	29,000	5,270	1,360	31
Geom. Mean	8,600	2,120	1,715	114

Geometric means of the counts are given in the table, since these are superior to arithmetic means for averaging bacterial counts, as has been shown by Robertson, 1932, and others. Obviously, in comparing data obtained with samples from the middle of the cores, for example, an arithmetic mean would give a result far too high to be representative of the series of eight samples.[3] The geometric means, on the other hand, indicates more nearly the general trend of the data. A comparison of the geometric means of all samples shows a decrease in bacterial count from the surface of the deposit downward, very few aerobic or facultative bacteria being found in the depths of the mud.

It is interesting to note that the figures obtained by Henrici and McCoy (1938), shown below, agree very closely. Their counts on Crystal Lake mud were obtained in 1935 and are expressed as number per cubic centimeter of wet mud rather than per gram of dry mud:

Counts of Bacteria of Crystal Lake Mud Samples, per Cubic Centimeter

Depth in cm.	Organisms per cc.
0	9000
3	1200
6	1000
9	1200
12	440
18	140

Only one core of Crystal Lake mud was studied at that time and its microflora was found to be similar to that of other oligotrophic lakes of the region.

The occurrence of anaerobic bacteria in the mud is shown in Table 2. The figures were obtained by reference to the adapted McCrady table given by Buchanan and Fulmer, 1928, and represent averages of the dilution counts found by use of cornmash and Bacto-beef media. Many of the figures are followed by a (+) sign, to indicate that the number stated is probably a minimum. It will be seen that the anaerobic counts decreased with increasing depth, in much the same manner as did the aerobic

[3] The count of 200,000 in core III may have been due to a bit of decomposing organic matter.

counts. Since this is so, it may therefore be concluded that some factor other than lack of oxygen is responsible for low aerobic bacterial counts in deep mud samples.

TABLE 2.—*Summary of anaerobic dilution counts of samples taken from the mud deposits of Crystal Lake (bacteria per gram of dry mud)*

Core	Sludge	Top	Middle	Bottom
I		2500+*	30+	0
II	3000+	260	45+	0
III	2800+	225	0	0
IV	2600+	40	55+	5+
V	2000+	210	0	
VI	1200+	290	0	0
VII		60	10+	5+
VIII	1750+	1400+	10+	10+
Geom. Mean	2125+	275+	7+	2+

* A (+) sign indicates that the number it follows is probably a minimum count.

The occurrence of other physiological groups of bacteria in the mud samples is shown in Table 3. Urea-fermenters were found to be quite abundant in the top samples of mud, but entirely absent in the bottom portions of the cores. Denitrifying bacteria, on the other hand, are apparently more abundant in the bottom samples than in those at the surface. No aerobic cellulose-fermenting bacteria were found and under the conditions of the analyses anaerobic cellulose-fermenters and organisms capable of attacking pectin were rarely noted.

DISCUSSION

At least two points are evident from this work. First, both aerobic and anaerobic counts are much higher in the sludge and top mud samples than in the deeper material. This is in confirmation of recent reports on mud of other lakes by Williams and McCoy, 1935, and by Henrici and McCoy, 1938, who found a definite decrease in bacterial count at greater depths in the mud deposits. In the second place, comparison of the counts from Crystal Lake mud with those from more eutrophic lakes shows a striking difference. Whereas the average count reported for Crystal Lake top mud is 2120 aerobic or facultative bacteria per gram, Williams and McCoy, 1935, found an average aerobic count of 5,200,000 per gram (dry weight) of top mud from Lake Mendota. Henrici and McCoy, 1938, reported an average of 609,300 bacteria per cubic centimeter of

TABLE 3.—*Occurrence of various physiological groups of bacteria in Crystal Lake mud**

	Sludge				Top				Middle				Bottom			
Core	Urea fermenters	Denitrifiers	Anaerobic cellulose fermenters	Pectin fermenters	Urea fermenters	Denitrifiers	Anaerobic cellulose fermenters	Pectin fermenters	Urea fermenters	Denitrifiers	Anaerobic cellulose fermenters	Pectin fermenters	Urea fermenters	Denitrifiers	Anaerobic cellulose fermenters	Pectin fermenters
I					−	−	−	−	−	−	−	−	−	+	−	−
II	+	+	−	−	+	−	−	−	+	−	−	−	−	−	−	−
III	+	−	−	−	+	−	+	−	+	+	+	−	−	+	−	−
IV	+	−	−	+	+	−	+	−	−	−	+	−	−	+	−	−
V	+	−	+	−	+	−	+	−	−	−	−	−				
VI	+	−	−	−	−	+	−	−	−	−	−	−	−	+	−	−
VII					−	−	−	−	−	+	+	−	−	+	−	−
VIII	+	+	+	+	+	+	−	+	+	+	−	−	−	−	−	−

* (+) means organisms present, (−) means organisms not found.

Lake Mendota mud. From data which these authors report the moisture content of their samples was about 85 per cent, so the dry weight count of aerobic or facultative bacteria is approximately 4,000,000 per gram.

Anaerobic counts likewise show great differences between the two lakes, Williams and McCoy reporting 100,000 anaerobes per cubic centimeter of top mud, which may be compared with the count of 275+ per gram obtained in similar Crystal Lake samples.

Lake Mendota differs from Crystal Lake in being composed of hard water and in being highly productive. Chemical analysis of water and mud from the two lakes has shown the composition presented in Tables 4 and 5. Relative hardness of the water is clearly indicated by the data for SiO_2, Ca and Mg. Particularly to be noted are the figures for organic material in the dry residue. Lake Mendota water contains over four times as much organic mater as does Crystal Lake. Mud from the latter lake is composed largely of fine sand and silt, a fact which is demonstrated by the high content of SiO_2. However, the most striking differences between the muds of the two lakes is the large amount of calcium in Lake Mendota. This is bound chiefly as the carbonate.

TABLE 4.—*Chemical composition of Crystal Lake and Lake Mendota water*[1]

	Milligrams per liter	
	Crystal Lake	Lake Mendota
SiO_2	0.08	3.3*
CaO	0.90	33.6*
MgO	1.00	37.6*
Dry residue	12.3	194.3
Inorganic	9.1	180.7
Organic	3.2	13.7
Plankton	0.75	2.91

[1] Results of chemical analyses were supplied by Dr. C. Juday except where marked (*), which were taken from Black, 1929.

The relative productivity of the lakes is shown by the fact that the plankton content of Lake Mendota water is over two and one-half times that of Crystal Lake water. Furthermore, several analyses have been made to determine the bacterial counts of the water in both lakes. Average results obtained by Fred, Wilson and Davenport, 1924, indicate the bacterial content of Lake Mendota water to be between 200 and 500 per milliliter. Counts on Crystal Lake water by Stark, 1936 (unpublished), Stark and McCoy, 1938, Henrici and McCoy, 1938, and by the author have given average bacterial counts between four and 80 per milliliter.

Henrici and McCoy, 1938, have suggested that the bottom bacteria are active only at the mud-water interface and are dying below. This is a logical conclusion if they are dependent upon

TABLE 5.—*Chemical composition of Crystal Lake and Lake Mendota bottom deposits*[1]

Lake	Sample	Depth of water	Position in core	Per cent of dry weight				
				SiO_2	FeO_3	Al_2O_3	CaO	MgO
Crystal[2]	1	20 m.	Ekman	41.21	1.88	2.64	0.33	0.02
	6 (XXI)	18 m.	Top	49.96	2.71	13.16	1.59	0.80
	6 (XXII)	18 m.	Middle	64.25	0.82	16.17	2.37	1.45
	6 (XXIII)	18 m.	Bottom	74.02	2.35	22.27	1.66	1.62
Mendota		24 m.	Ekman	36.32	4.67	8.28	19.88	1.85

[1] Data for Crystal Lake supplied by Dr. C. Juday and Dr. W. H. Twenhofel; those for Lake Mendota taken from Black, 1929.

[2] Sample No. 1 taken July 17, 1927, and analyzed in 1937. Samples No. 6 (XXI, XXII, XXIII) taken in August, 1937, and analyzed in 1937–1938.

materials of the bottom for their nutrition. Therefore, the fact that the number of viable bacteria in the upper samples of Crystal Lake mud is small may be definitely correlated with the low concentration of organic and mineral nutrients available in the bottom water and surface materials of the bottom.

SUMMARY

1. Twenty-nine mud samples representing eight cores from Crystal Lake in Northern Wisconsin have been studied with respect to their content of aerobic, facultative, and anaerobic bacteria.

2. Both groups of bacteria show a decrease in number at increasing depths below the surface of the bottom mud.

3. Bacterial counts in Crystal Lake (oligotrophic) mud are much lower than similar reported counts in Lake Mendota (eutrophic). This is considered due to the lower amount of organic and mineral nutrients available in the water.

The author is indebted to Dr. W. H. Twenhofel for the opportunity of being associated with this work, and to Dr. Elizabeth McCoy for helpful criticism and suggestions.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 9, NO. 1, PP. 8–13, FIG. 1, TABLES 1–2, APRIL, 1939

SHOAL-WATER DEPOSITS OF THE BERMUDA BANKS*

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ABSTRACT

Mechanical analyses of pure calcareous sediment from the Bermuda Banks show a correlation between mechanical composition and topographic location. Beach sands are well sorted and uniform, lagoon sediment is fine and slightly less well sorted, and the sands of the exposed boundary reef are coarse. The size frequency distributions are similar to those to be expected in inorganic sediment produced by the sea in like environments.

INTRODUCTION

The present study of recent calcareous bottom deposits off the Bermuda Islands was undertaken with a two-fold purpose: (1) to determine any correlation existing between mechanical composition and topographic location, and (2) to add to the few existing analyses of pure calcareous sediment to determine whether such material is similar in mechanical composition to inorganic sediments of like environment. The samples were collected in 1934 by Mr. H. C. Stetson with these two purposes in mind and were later placed at the disposal of the writer for analysis. Invaluable aid was given by Mr. Stetson throughout the laboratory work and during the preparation of the manuscript.

The isolation of the Bermuda Islands from any land mass precludes the addition of any appreciable amount of inorganic detritus to the sediment (Sayles, 1931). The Islands themselves as well as the surrounding reefs are completely calcareous. The area is well chosen for a study of present sedimentation for all material is produced, transported, and deposited in this one place under observable conditions. The "controls" are, therefore, all known and no factors are left to be explained as characteristics resulting from past and only partially known environments. The present areas of sedimentation of the Bermuda Banks (Fig. 1) lend themselves to classification in five topographic divisions, (1) the beaches, (2) the inner, more or less enclosed lagoons, (3) the outer lagoon, (i.e. the area of shoals and flats within the boundary reef), (4) the boundary reef, and (5) the area outside the reef and within the 100 meter line.

* Contribution 191 of the Woods Hole Oceanographic Institution.

PREVIOUS WORK

Previous work on the recent sediments of the Bermudas is limited to that of Bigelow (1905). He, however, approached the study almost wholly from the viewpoint of the organic derivation of the sediment. He used topographic divisions similar to those above, and though without mechanical analyses, made valuable observations upon grain size and its relation to topography as well as to its source.

Three other studies of mechanical analyses of calcareous sediments have come to the attention of the author. Bramlette (1926) studied thirty samples from Pago Pago Harbor, Samoa. The deposits of the reef flats and slopes are very poorly sorted, with a wide range in sizes, but with only a negligible quantity of material below very fine sand size. The silts of the deeper quiet waters of the inner harbor and the fine sands at the mouth of the harbor are much better sorted than the reef deposits. These conclusions are not all in accord with those of the present investigation. The two areas are however not completely com-

parable, one being localized in a single harbor and receiving appreciable amounts of inorganic detritus, the other covering a much greater range of environments and containing only calcareous material. There is a similarity between the two

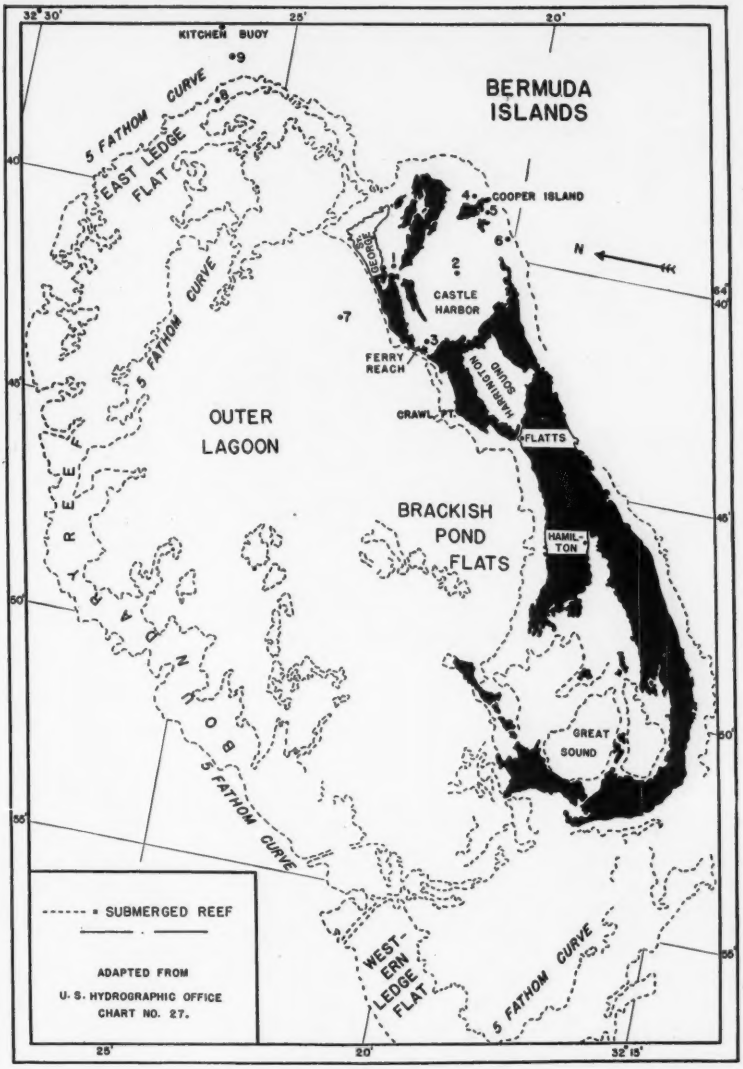

FIG. 1.—Map of Bermuda Islands.

studies however, in the relative coarseness of the sediment on the reef. Bramlette's observation "that a considerable proportion of the material is not comminuted, but remains the size of the original contributing element, and such material when not sufficiently reworked, shows sizes depending to this extent on the contributing materials at the particular place," seems an important concept in the study of detritus of organic origin. It may possibly be used to explain the erratic nature of the statistical constants of one or two of the Bermuda analyses.

Vaughan (1918) analyzed twenty-five samples from Murray Island, Australia; Florida; and the Bahamas. The beaches of Murray Island and Florida contain coarser material than the Bermuda beaches. In comparison with the lagoon sediments of Bermuda the lagoon sands of Australia are coarse, the Florida lagoon deposits similar and the Bahaman bight sediments fine. In all the samples except those of the land-locked areas of the Bahamas, such as South Bight, the clay-silt fractions form a very small per cent. Their absence is ascribed to the winnowing action of currents. A similar lack of fine material, probably resultant from the same cause, is noted in two of the topographic divisions of the Bermuda Banks (Table 2).

Thorp (1936) also finds that in pure calcareous sediments of the Pearl and Hermes Reef the coarsest material lies on or near the reef proper. Five samples are actually gravels (over 50% coarser than 2 mm.). There is a gradual decrease in the size of the material toward the center of the lagoon, but even here, the clay-silt fraction totals less than 18%. The deficiency of fine particles is explained by their easy removal into the deeper waters outside the reef because of the prevailing set of the currents. This study most closely parallels the present one in type of area and results.

MECHANICAL ANALYSES

The laboratory procedure for the analysis of samples containing only material of sand grades and coarser consisted of the removal of salts through repeated washings, sieving for fifteen minutes in a nest of Tyler Standard Screens and the weighing of the separated fractions. Samples containing material in the clay-silt sizes were wet-sieved through the 200-mesh screen. The coarse separate was treated as above. The fine material was freed of salt by a vacuum pump and a series of Pasteur filters and then analyzed according to the pipette method of Krumbein (1932, 1935). Data thus obtained were plotted as cumulative curves, and the median, and Trask's (1932) coefficients of sorting and skewness were determined. These are recorded in Table 1.

From this table it is observed that the beach samples are the most uniform group, with an average median of 0.283 mm., a *So* of 1.28 and a *Sk* of 1.03. The medians are the smallest found in any of the five topographic divisions. All of the beach samples, however, come from one locality, Cooper Island. It is probable that the key to the fineness here has been found by Bigelow (1905, p. 567). He notes that most of the Bermuda beaches are swept clean of calcareous silt, but that some, among them those of Cooper's Island, consist of typical shell sand plus large proportions of calcareous material derived from the destruction of neighboring cliffs. The ledges and cliffs of the Bermuda Islands are all formed of eolianite, a lithified dune sand. The assumption that the mechanical composition of the eolianite is similar to that of the dune sands now forming, seems fair. The very close agreement of the statistical constants of the modern dune sand and beach deposits (Table 1) certainly suggests that the source of the beach material is at least in part the eolianite. Hence the beaches of Cooper Island may show fine medians because of their derivation to a large extent from a wind worked sand, and other Bermuda beaches composed of shell sands in the first cycle of sedimentation, may be coarser. They might then agree with

TABLE 1.—*Statistical Constants*

	No.	Station Location	Depth in Ft.	Q_1 mm.	M mm.	Q_3 mm.	*So*	*Sk*	Log *Sk*
Beach		High tide, Cooper's I. Bar N. End		.38	.28	.22	1.33	1.08	.03
		High tide, Cooper's I. Bar S. End		.29	.24	.21	1.19	1.08	.03
		Low tide, Long Bay Beach, Cooper's I. N. End		.66	.47	.32	1.44	.94	−.03
		Low tide, Long Bay Beach, Cooper's I. S. End		.37	.27	.21	1.33	1.07	.03
		Off-shore, Long Bay Beach, Cooper's I.	2–3	.26	.21	.17	1.25	1.03	.01
		Dunes, Long Bay Beach, Cooper's I. Bar		.28	.25	.21	1.16	.97	−.02
Inner Lagoons	4	Cooper's I. off-shore	6	.24	.21	.19	1.24	1.04	.02
	2	Castle Harbor	30	2.25	1.30	.67	1.84	.89	−.05
		Harrington Sound	48	.92	.25	.04	1.56	.58	−.24
	3	Ferry Reach	20	.92	.56	.21	2.09	.62	−.21
	1	St. George's Harbor	42	.02	.014	.011	1.35	.98	−.01
Outer Lagoon		Crawl Point	24	.76	.56	.42	1.35	1.01	.00
		Brackish Pond Flats	6	.91	.65	.47	1.39	1.01	.00
		Outside Brackish Pond Flats	42	1.25	.61	.08	1.25	.27	−.57
		Outside Murray Anchorage	48	1.10	.70	.38	1.70	.85	−.07
	7	Murray Anchorage	49	.63	.20	.03	4.51	.49	−.31
		Outside Flatts Harbor	28	.84	.55	.26	1.82	.71	−.15
Boundary Reef	5	Inside Reef, Cooper's I.	30	.40	.31	.28	1.19	1.13	.05
	8	East Ledge Flat	24	1.05	.72	.50	1.45	1.02	.01
	9	Kitchen Buoy Reef	60	1.05	.77	.57	1.36	1.01	.00
Outside Reef	6	Outside Reef, Cooper's I.	69	1.00	.70	.58	1.32	1.18	.07
		Kitchen Buoy	54	.20	.14	.11	1.35	1.12	.05

Vaughan's analyses, in which the beach sands were the coarsest of those of any of his environments.

It may be noted in passing that the samples taken at low tide are more poorly sorted and with coarser medians than those taken at high tide. This accords with the findings of Schalk (1938) for the beaches of Cape Cod, but is the reverse of that of Bramlette (1926) for the Aua Reef sands of Samoa.

The first analysis (No. 4) of the inner lagoon group, quite characteristically belongs with the beach sands. This is explained by its position immediately offshore in only six feet of water. All other inner lagoon samples have a negative log. *Sk*, denoting a frequency curve which tails off farther in the direction of the fine sizes. Though quantitative data are lacking, undoubtedly a very important factor in the reduction of detritus to fine sizes is the passage of bottom sediment through the alimentary tracts of benthonic organisms, especially holothurians. The lagoons are the chosen habitat of such animals.

Castle Harbor sediment is coarser than the other inner lagoon samples. Its median shows it, in fact, to be a fine gravel. Although Castle Harbor is an enclosed lagoon it maintains free communication on all sides with the ocean. Protection from storm waves is thus provided without destroying circulation, and it is therefore a very favorable location for the growth of marine organisms. An abundance of empty shells and organic fragments, which are but little waterworn, give evidence of recent and rapid

TABLE 2.—*Size Fractions*

	No.	Station Location	Gravel 30–1 mm.	Sand 1–.05 mm.	Silt .05–.005 mm.	Clay .005–.001 mm.	Colloid .001–0 mm.
Beach		High tide, Cooper's I. Bar N. End	0	100	0	0	0
		High tide, Cooper's I. Bar S. End	0	100	0	0	0
		Low tide, Long Bay Beach, Cooper's I. N. End	8	92	0	0	0
		Low tide, Long Bay Beach, Cooper's I. S. End	0	100	0	0	0
		Off-shore, Long Bay Beach, Cooper's I.	0	100	0	0	0
		Dunes, Long Bay Beach, Cooper's I. Bar	0	100	0	0	0
Inner Lagoons	4	Cooper's I. off-shore	0	100	0	0	0
	2	Castle Harbor	60	32	4	3	1
		Harrington Sound	22	48	22	6	2
	3	Ferry Reach	21	68	6	3	2
	1	St. George's Harbor	0	0	95	3	2
Outer Lagoon		Crawl Point	15	85	0	0	0
		Brackish Pond Flats	20	80	0	0	0
		Outside Brackish Pond Flats	33	45	13	6	3
		Outside Murray Anchorage	30	68	0.5	0.5	1
	7	Murray Anchorage	10	61	28	0.5	0.5
		Outside Flatts Harbor	12	81	2.5	2	2.5
Boundary Reef	5	Inside Reef, Cooper's I.	0	100	0	0	0
	8	East Ledge Flat	28	72	0	0	0
	9	Kitchen Buoy Reef	28	72	0	0	0
Outside Reef	6	Outside Reef, Cooper's I.	25	75	0	0	0
		Kitchen Buoy	2.5	83.5	8	6	0

accumulation. The somewhat poorer sorting also supports the absence of extensive reworking and attrition. Thus the effect of the original size of the contributing element may be a factor here in explaining the coarseness of the sediment. A second factor is the removal, by tides and currents, of whatever fine material may be formed; for Castle Harbor is too exposed and too large to permit the existence of the quiet water necessary for the settling out of particles of clay and silt sizes. These fine sizes can find ultimate lodging only when carried into more nearly land-locked basins such as St. Georges Harbor. The sediment there is, in fact, fine and extremely well sorted, supporting the idea of longer transport and selective deposition. That the fineness of the material is to be explained by the influx of much material of subaerial erosion (Bigelow, 1905, pp. 268–269) seems improbable because of the lack of surface drainage throughout the Bermudas and because of a lack of vigorous wave action in a lagoon of such limited dimensions as St. Georges Harbor.

The samples of the outer lagoon, with the exception of that of Murray Anchorage, are coarser than those of either of the preceding environments. The deviation of this one sample is reflected in sorting and skewness as well as in the median, and is not readily explained. It may be due merely to chance sampling. The other samples show a high degree of uniformity in both size and sorting. The average median is 0.61 mm. *So*, 1.503,

and *Sk*, 0.849. There are positive and negative values for log. skewness, but the negative ones are much greater.

The boundary reef contains the coarsest sediment of any of the environments, with the exception of the Castle Harbor gravel which has been explained above. Though the medians are not much larger than those of the outer lagoon samples, a difference exists between the sediments of the two areas. Table 2 indicates that clay and silt sizes are entirely absent on the reef. This is due to its exposed position. The fineness of sample No. 5 may again be due to chance sampling in the lee of a ledge or some other protected spot.

The two samples taken beyond the reef diverge noticeably in their coefficients. One resembles the sediment of the reef itself, the other is inexplicably fine.

From the data it is clear that in general a correlation does exist between mechanical composition and topographic location. The lagoons are areas for the accumulation of fine sediment. The reef sediment is coarse both because it is the source of supply and because it is subjected to the most severe wave and current action of any of the environments. The beaches, as is customary, are the seat of excellent sorting and uniformity. There are of course exceptions to these generalizations, such as occur in any suite of samples, and conclusions must be drawn only from general trends.

The medians of the entire group of samples range from 0.77 mm. to 0.14 mm., with the exception of the Castle Harbor gravel and the St. Georges Harbor silt. Thus the samples are all medium or fine sand. The sorting is good everywhere except at Murray Anchorage, some samples being even extremely well sorted. The range 1.19 to 2.09 falls wholly below Trask's upper limit of 2.5 for good sorting. Good sorting is an indication of the activity and uniform competency of the present agents of erosion, transportation and deposition, and of the adjustment of a sediment to its present environment. Approximately one-half of the samples show a $-\log. Sk$ and one-half a $+\log. Sk$. This agrees with Trask's analysis of samples from all over the world in which skewness tended to be symmetrical about unity.

It may therefore by concluded that calcareous materials obey the same laws as inorganic materials, and result in sediments of similar mechanical composition; and that the sea will produce, under given conditions, sediments of like nature regardless of differences in source and type of supply.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 9, NO. 1, PP. 14–19, FIGS. 1–5, APRIL, 1939

THE OCCURRENCE OF SPORE COAL IN THE WILLIAMSTON BASIN, MICHIGAN

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In the fall of 1933 the Davidson Coal Company opened up a pit for the mining of coal in the district directly south of the brick plant, one-quarter mile east of the village of Williamston in Ingham County, Michigan (fig. 1). The area is situated in the Saginaw formation of Pennsylvanian age near the southeast margin of the major coal basin. Logs of borings which were made available appeared to indicate that the layer of higher coal especially was restricted to a local and

FIG. 1.—Map of Michigan, showing outline of the coal basin and location of the Williamston area (after W. A. Kelly).

somewhat isolated basin. This was also the conclusion reached, after the removal of overburden had laid bare the greater portion of the upper seam.

they were uncovered in the stripping process. Shortly after the section at Station 8 (fig. 2) in the extreme west end of the pit had been exposed, two thin seams

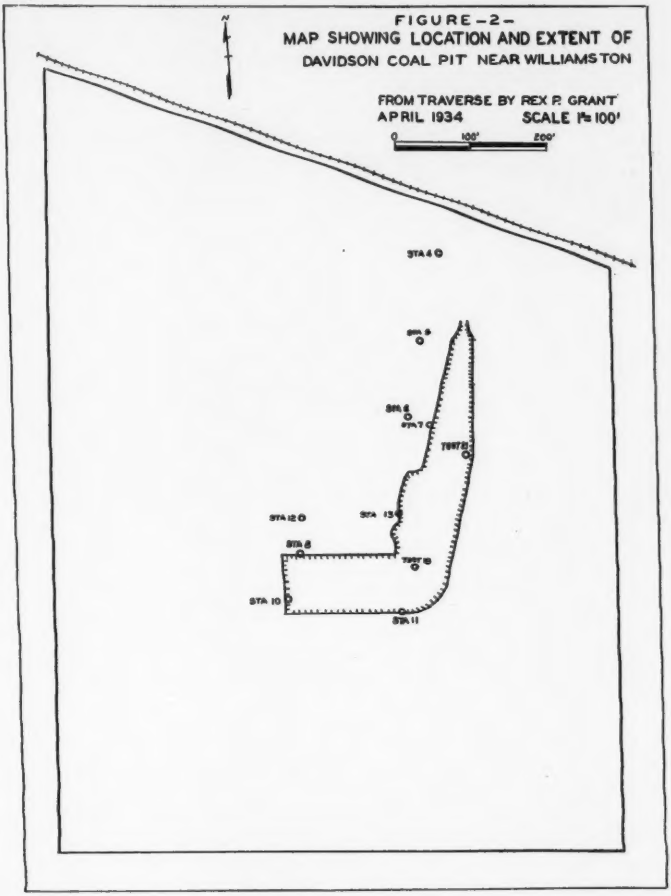

FIG. 2.

Through the several years that coal mining operations were in progress the writer, together with several of his advanced students, made numerous trips into the area to study the exposures as

of coal made up largely of compressed spores were uncovered. The upper layer of spore coal, eight inches thick, occurred between beds of shale at a depth of twelve to fourteen feet below the surface,

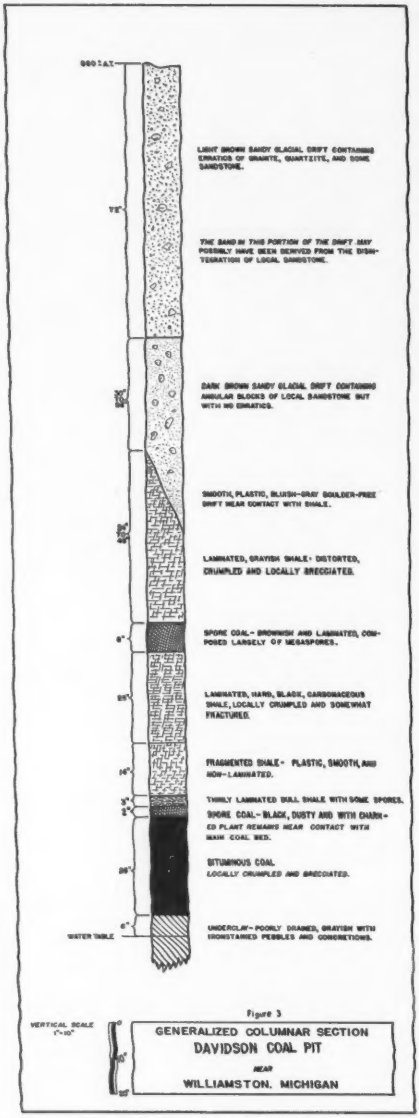
LIGHT BROWN SANDY GLACIAL DRIFT CONTAINING ERRATICS OF GRANITE, QUARTZITE, AND SOME SANDSTONE.
THE SAND IN THIS PORTION OF THE DRIFT MAY POSSIBLY HAVE BEEN DERIVED FROM THE DISINTEGRATION OF LOCAL SANDSTONE.
DARK BROWN SANDY GLACIAL DRIFT CONTAINING ANGULAR BLOCKS OF LOCAL SANDSTONE BUT WITH NO ERRATICS.
SMOOTH, PLASTIC, BLUISH-GRAY BOULDER-FREE DRIFT NEAR CONTACT WITH SHALE.
LAMINATED, GRAYISH SHALE- DISTORTED, CRUMPLED AND LOCALLY BRECCIATED.
SPORE COAL- BROWNISH AND LAMINATED, COMPOSED LARGELY OF MEGASPORES.
LAMINATED, HARD, BLACK, CARBONACEOUS SHALE, LOCALLY CRUMPLED AND SOMEWHAT FRACTURED.
FRAGMENTED SHALE- PLASTIC, SMOOTH, AND NON-LAMINATED.
THINLY LAMINATED DULL SHALE WITH SOME SPORES.
SPORE COAL- BLACK, DUSTY AND WITH CHARRED PLANT REMAINS NEAR CONTACT WITH MAIN COAL BED.
BITUMINOUS COAL
LOCALLY CRUMPLED AND BRECCIATED.
UNDERCLAY- POORLY DRAINED, GRAYISH WITH IRONSTAINED PEBBLES AND CONCRETIONS.
WATER TABLE
VERTICAL SCALE
Figure 3
GENERALIZED COLUMNAR SECTION
DAVIDSON COAL PIT
NEAR
WILLIAMSTON, MICHIGAN

FIG. 3.

or at an elevation of approximately 846 feet above sea level (fig. 3). As mining operations progressed it was found that the two beds of spore coal persisted throughout the entire extent of the small, restricted basin.

The capping layer of shale, ranging in thickness from 24 to 46 inches, is present immediately below the glacial drift. It is grayish, thinly laminated, and smooth, and displays many features of distortion, *crumpling, and local brecciation as direct* reflections of movement related to pressure of the Pleistocene ice sheets which deployed over the region. Directly below the upper seam of spore coal is a layer, 25 inches thick, of thinly laminated, dark-colored, carbonaceous shale. Although somewhat harder and more compact than the bed above, this layer likewise displays the features of crumpling and fracturing resulting from ice activity.

Immediately below this thin-bedded stratum is a 14-inch bed of plastic, nonlaminated, and distinctly fractured shale. It is underlain by 3 inches of thinly laminated, dull gun-metal gray shale, containing scattered spores, below which was found a second seam of spore coal with a thickness of merely a few inches. This lower, highly sporiferous layer occurs at a depth of about 17 feet below the surface, or 4 feet below the upper spore bearing seam. It rested directly upon a 26-inch bed of bituminous coal, which in turn is underlain by a grayish underclay containing an abundance of iron-stained concretionary pebbles and fragments of plant remains.

The main bed of bituminous coal shows considerable variation in thickness, ranging from merely a few inches to 6 or 7 feet. It is not especially uniform in either character or quality, and where exposed over a large area in the floor of the quarry, it appears nowhere to be horizontal, but displays rather, a gently rolling attitude. Locally, it is arched, crumpled, and brecciated (fig. 4), and in certain limited areas it has been pulverized into coarse slack owing to slight

horizontal movements induced in the formation by ice pressure.

Samples of the two thin seams of spore coal exposed in the area were studied in the laboratory and found to be made up of innumerable well-preserved megaspores loosely embedded in a ground mass of carbonaceous and shaly material (fig. 5A). The spores had been compressed (fig. 5B) into a compact and definitely laminated mass, somewhat soft and relatively low in specific gravity. In its natural environment the coal possesses a characteristic gun-metal gray color and feels greasy. Where exposed to weathering, however, the spores have a reddish-brown cast and stand out in prominent relief against the shaly carbonaceous groundmass. So loosely embedded are some of the spores in the coal that they may readily be separated from the matrix by means of a teasing needle.

Several samples of the spore coal were sent to a former student, George C. Sprunk (1), for purposes of comparison with eastern types. He proclaimed the material most interesting and, after some detailed studies of the spores, made the observation that "they appear to be of the same types as those occurring in the Elkhorn bed of Kentucky and the Taggart—No. 2 Gas, and Alma beds of West Virginia" (2). On the basis of spore content Sprunk classified the coal as belonging to the Upper Pottsville formation. This confirms the stratigraphic correlation which had previously been made for the coal of the area by W. A. Kelly (3). Lane (4) placed the coal measure of the Williamston area in the upper part of the Upper Verne, which corresponds to the Upper Pottsville formation.

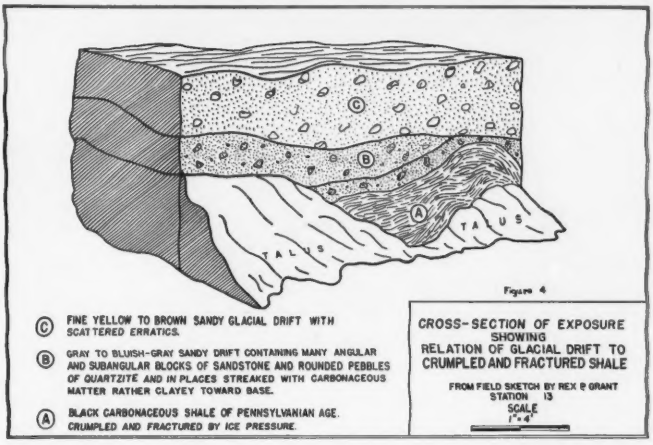
C
B
A
TALUS
TALUS
Figure 4
C FINE YELLOW TO BROWN SANDY GLACIAL DRIFT WITH SCATTERED ERRATICS.
B GRAY TO BLUISH-GRAY SANDY DRIFT CONTAINING MANY ANGULAR AND SUBANGULAR BLOCKS OF SANDSTONE AND ROUNDED PEBBLES OF QUARTZITE AND IN PLACES STREAKED WITH CARBONACEOUS MATTER RATHER CLAYEY TOWARD BASE.
A BLACK CARBONACEOUS SHALE OF PENNSYLVANIAN AGE. CRUMPLED AND FRACTURED BY ICE PRESSURE.
CROSS-SECTION OF EXPOSURE SHOWING RELATION OF GLACIAL DRIFT TO CRUMPLED AND FRACTURED SHALE
FROM FIELD SKETCH BY REX B GRANT
STATION 13
SCALE
1" = 4'

FIG. 4.

The glacial drift cover of the area provides a study of special interest. In the section referred to, the mantle of drift ranges in thickness from 8 to 10 feet and rests directly on the Pennsylvanian shale. The upper 6 feet of light brown sandy glacial till contains numerous erratics of well-rounded and polished boulders of granite and quartzite, together with scattered pebbles of limestone.

The lower 3 to 5 feet of the drift is likewise sandy but contains an abundance of angular blocks of locally derived ferruginous sandstone. The presence of the sandstone, referred by Kelly (5) to

the Grand Rapids group, and the almost complete absence of erratics seem to indicate that this portion of the drift was laid down by an ice sheet the activity of which was somewhat localized. The overlying drift, with its foreign boulders, suggests a readvance of the ice following an episode of apparent stagnation. The basal 10 to 12 inches of the drift, near its contact with the underlying shale, is bluish gray, smooth and somewhat compacted. It is composed of boulder free clay, which was undoubtedly derived from the erosion of the shale upon which it rests.

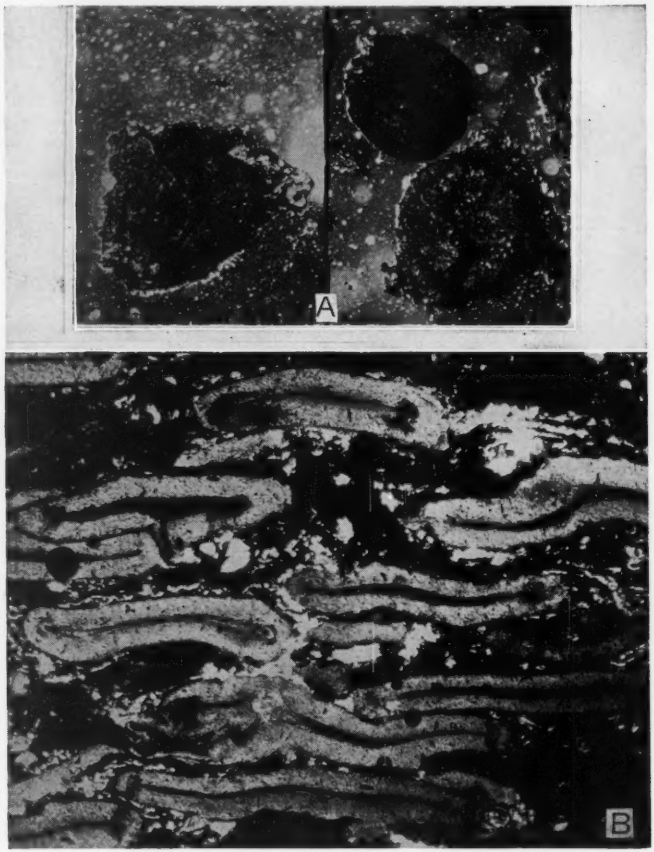

FIG. 5.—*A*, Megaspores (top section); photographed by Keith K. Kreag. *B*, Cross section of coal showing compressed spores and the laminated character of the material; photographed by George C. Sprunk.

The unconformable contact between the basal drift and the coal-measure shale is marked by an erosional surface which

suggests either an interval of long-continued pre-glacial erosion or the removal of much of the formation by ice in the early stages of Pleistocene activity. The writer is of the opinion that the ice pressures of the oscillating lobes which deployed over the area were more or less responsible for the compaction of the spores into the laminated shaly spore coal which comprises the two seams.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 9, NO. 1, PP. 20–27, FIGS. 1–3, APRIL, 1939

IGNEOUS AND METAMORPHIC ROCKS FROM PLEISTOCENE GRAVELS OF CENTRAL LOUISIANA

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ABSTRACT

Igneous and metamorphic rock types are found in gravels at the base of each of four distinct series of fluviatile deposits making up the four Pleistocene depositional terraces of Louisiana. Their rarity in exposures is accounted for by intense surface weathering. The igneous and metamorphic rock types appear to have been transported from the Lake Superior Upland and igneous areas of the Central Interior region. Their presence far south of their source and their peculiarities of size and roundness are attributed to the specialized and fluctuating conditions of Pleistocene time.

INTRODUCTION

In central Louisiana very few exposures of the so-called Citronelle formation have yielded igneous or metamorphic rock fragments. At the surface over 95 per cent of the coarse elements in these deposits consist of chert. It was with considerable interest, therefore, that the writer collected a variety of igneous and metamorphic rock types from the commercial gravel pits of the region. These rocks, dredged from depths of 40 to 60 feet and forced to the surface by large centrifugal pumps, are comparatively fresh and show little effect of weathering. The presence of these igneous and metamorphic rocks in greater abundance at depth suggests that these rock types were once disseminated throughout all the gravel beds, their rarity in exposures being due to the intense surface weathering in this region.

A list of the rock types represented in the gravels is published at this time because of its possible bearing on the origin, depositional agents, and source areas of the deposits in which they are incorporated. It is hoped that geologists and petrographers in other sections of the country may be able to restrict certain of the rocks, or groups of rocks, to more localized areas than those suggested here.

The writer is indebted to Mr. H. E. Shull, Plant Superintendent, Belle Cheney Springs gravel pit, Gifford-Hill Construction Co., for information concerning the gravels at that pit; and to Mr. Truman P. Woodward and Mr. Albert Gueno, field men of the Minerals Division of the Louisiana Department of Conservation, for collecting igneous and metamorphic gravels from the Belle Cheney Springs gravel pit and for calling attention to the wide variety of gravels brought to the surface at that locality.

GENERAL GEOLOGICAL RELATIONSHIPS AND AGE OF THE GRAVELS

The surface geology of central Louisiana is dominated by a series of clays, sands, and gravels which unconformably overlie Tertiary deposits. Geologists early divided these materials into two formations: an older Lafayette (Citronelle) formation, consisting of coarse materials; and a younger Port Hudson (Columbia) formation, consisting of fluviatile sands and clays.

Recent field work by the writer (1) shows that in central Louisiana the group of sediments included in the Citronelle and Port Hudson formations may be separated into four distinct series of fluviatile deposits which form well-defined depositional terraces. The terraces, and their underlying deposits, have been named (from youngest to oldest) Prairie, Montgomery, Bentley, and Williana. These names are derived from localities

in Grant and La Salle Parishes where the terrace surfaces are well preserved.

Each of the four depositional units (and the Recent flood-plain sediments) was laid down in valleys cut in Tertiary or older terrace materials. Active regional tilting occurred during the different stages of alluviation and the intervening stages of valley cutting. As a result, the terraces now converge seaward and diverge landward.

The landward divergence of the terraces exposes the basal part of the three older terrace deposits, making it possible to reconstruct the sequence of deposition within each unit. Data from wells drilled through Prairie terrace and Recent flood-plain deposits show a comparable sequence of deposition to that exposed in the older fluviatile units. The general relationship of the fluviatile terraces is shown in Fig. 1.

Each depositional unit grades from a coarse, lenticular, gravelly basal phase, through sands, to poorly sorted silts with interfingering clays near the top of the sequence. The sediments in the upper part of the sequence in all of the terrace deposits are lithologically similar to those deposited along natural levees and in the backwater swamp areas of the modern flood plains.

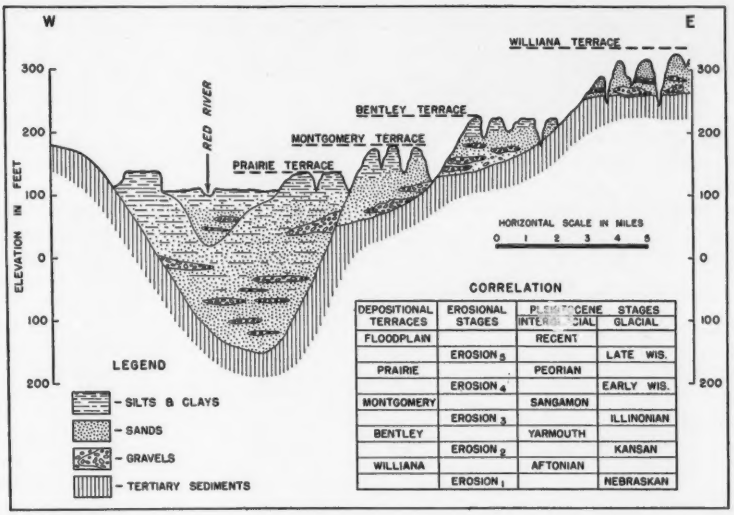

FIG. 1.—Generalized relationships of the four depositional terraces present along the eastern side of the Red River valley in northwestern Grant Parish. Correlation with glacial and interglacial stages is indicated. For location of Grant Parish see Fig. 3.

The writer (1) has tentatively correlated these four epochs of deposition with the Pleistocene interglacial stages and the erosional epochs with the glacial stages. (See fig. 1.) These epochs must have been controlled by four distinct oscillations in sea level, apparently corresponding to the worldwide fluctuations in oceanic level which accompanied the glacial period. During glacial stages, the formation of ice on the land from sea water left the oceanic level low, streams were rejuvenated, and the valleys were cut. During interglacial stages, the

oceanic level was raised by melting of the ice sheet. The base level of streams was thus gradually raised and great flood plains were constructed within the valleys cut during the preceding erosion stage. The fluviatile terraces extend up major streams (fig. 3) as large trains of coarse debris. Typical trains are traceable along the Mississippi, Ouachita, Red, and Sabine rivers. Coastward these fluviatile terraces merge with their deltaic equivalents, forming a great coastwise band of Pleistocene gravels, sands, and clays. Little River, Calcasieu River, and many other tributaries were developed upon the Pleistocene deltaic plains during one or another stage of Pleistocene rejuvenation. These smaller streams reworked the older terrace materials and concentrated the coarser particles along their courses during the later Pleistocene stages.

IGNEOUS AND METAMORPHIC ROCKS

The igneous and metamorphic rocks are found in greatest abundance near the base of each sequence of deposition. They vary in size and shape in much the same manner as do the chert particles which preponderate in all exposures. The basal gravels are in lenses and massive beds in which the sand-gravel ratio is about 50:50. In general the coarse elements are much larger than those higher in the deposit, some of the boulders at the base reaching 24 inches in diameter. Higher in the sequence the gravels occur as stringers within cross-bedded sand layers and as smaller lentils of finer gravel. The sand-gravel ratio in these beds averages about 70:30. Only a few thin lenses of pebbles occur within the upper 15 feet of typical deposits.

Size.—The coarser particles of the gravels vary from half an inch to more than 12 inches in diameter. Only those over 1 inch in diameter were collected for this study. For convenient reference, the collections were divided into two size groups, the smaller between 1 and 4 inches in maximum diameter, and the larger from 4 to 12 inches in maximum diameter. The larger cobbles and boulders are associated with petrified wood fragments, a few of which are over 24 inches long, and with locally derived quartzitic sandstones, some of which also reach 24 inches in diameter.

Roundness.—Most of the particles vary from angular to subrounded. The smaller granite, gneiss, and quartzite pebbles are well-rounded and nearly spherical. Most of the cobbles and boulders, particularly those of rhyolite and ferruginous chert found near the base of the deposits, are subangular; very angular ones are found only occasionally. Figures 2a and b show the typical range in roundness of particles chosen at random from the collection.

Two large angular specimens are definitely polished, with the development of one or more facets. The smoothness of these facets suggests glacial abrasion, although there are no striae or other evidence to support this suggestion. These specimens and other boulders are much larger than the average particles and show little effects of abrasion. Few are locally derived and most are foreign to the region. The lack of rounding and large size of boulders, together with facets suggesting glacial abrasion, indicate some other agent of transportation than streams. Apparently the only agent which could possibly have transported these larger "erratics" is occasional icebergs carried southward by streams from the glacial front.

Localities.—Specimens were collected from the following localities (shown by number on fig. 3).

1. Belle Cheney Springs gravel pit of Gifford-Hill Construction Co., near Turkey Creek, Evangeline Parish, La. [Prairie age].
2. Gravel pit of Gifford-Hill Construction Co., near Forest Hill, Rapides Parish, La. [Bentley age].
3. Gravel pit of Rapides Sand & Gravel Co., near Woodworth, La. [Williana age].
4. Gravel pit of the Alexandria Sand &

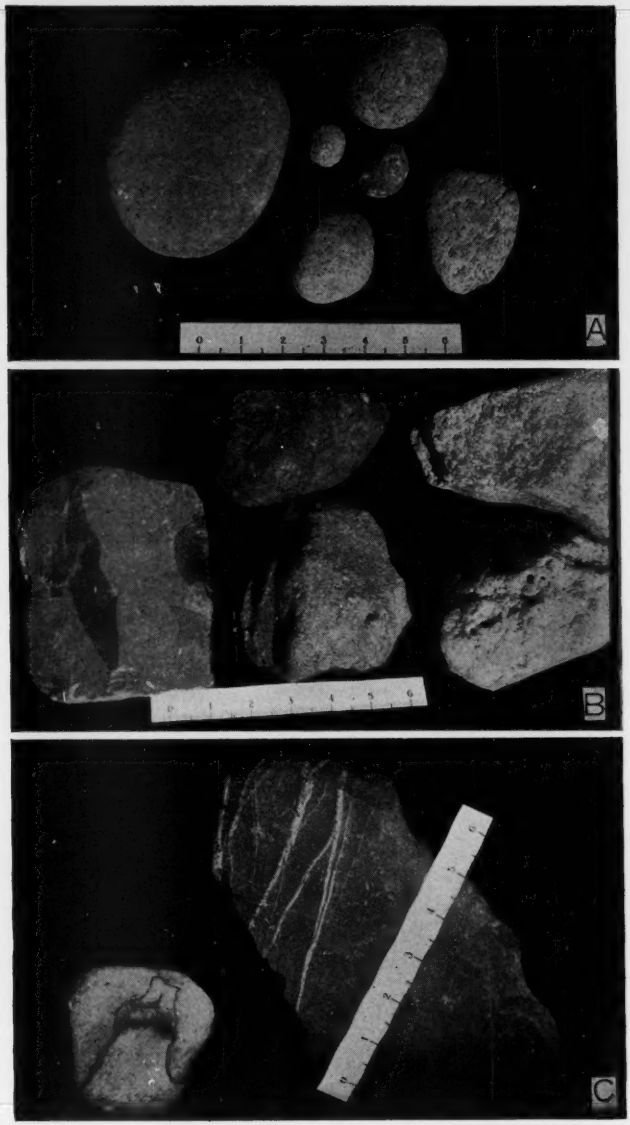

FIG. 2.—Photographs showing typical rounded gravels (*A*), typical angular and subangular particles (*B*), and polished and faceted rocks (*C*) which may indicate glacial abrasion.

Gravel Co., near Woodworth, Rapides Parish, La. [Williana age].

5. Exposure along Red River at the mouth of Bayou Maria, 2 miles east of Alexandria, Rapides Parish, La. [Bentley age].
6. Exposure in center of northeast line between irregular secs. 30 and 40, T. 6 N., R. 2 W., 5 miles south of Colfax, Grant Parish, La. [Bentley age].
7. Exposure in NW ¼ NW ¼ sec. 2, T. 7 N., R. 3 E., 5 miles south of Jena, La Salle Parish, La. [Williana age].
8. Abandoned gravel pit at Rhinehart, La Salle Parish, La. [Montgomery age].
9. Gravel pit of the Gifford-Hill Construction Co. at Sicily Island, Catahoula Parish, La. [Montgomery (?) age].
10. Pine Prairie salt dome, central Evangeline Parish, La. [Montgomery (?) age].
11. Avoyelles Hills, 2 miles northwest of Marksville, Avoyelles Parish, La. [Prairie age].

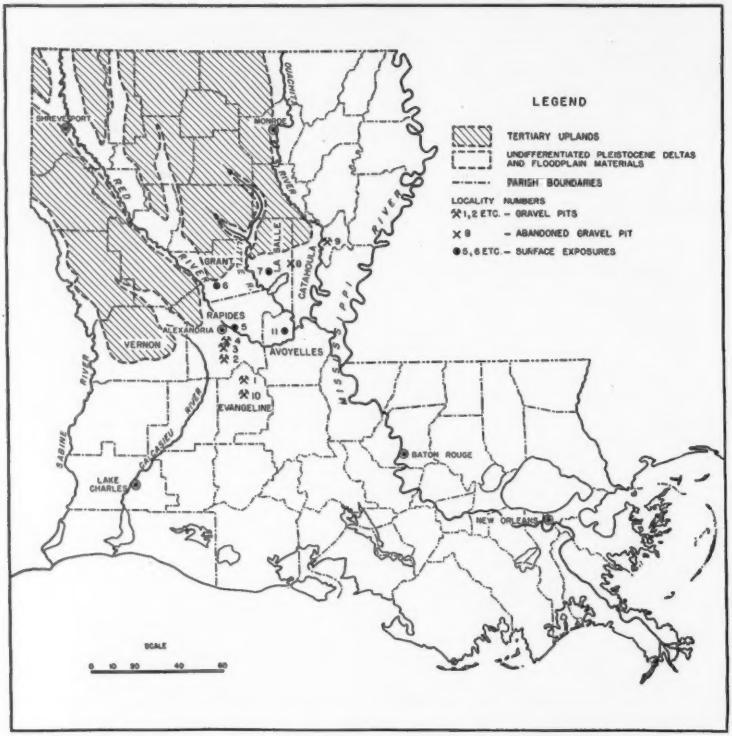

FIG. 3.—Map showing generalized extent of Quaternary deposits in Louisiana, and the localities from which igneous and metamorphic rocks were collected.

Rock Types.—A list of the rock types represented in the gravel collections is given below. It was compiled from a study of 26 thin sections made from as many different types of rocks as could be separated megascopically. The localities from which the various specimens were collected are indicated by the numbers following each rock name.

Igneous rocks
- Aphanites
  - Basalt, amygdaloidal (2)
  - Basalt (trachytoid, fine grained) (5)
  - Rhyolite porphyry (1, 2, 5, 8)
    - Devitrified (aporhyolite) (1, 2)
    - Spherulitic (partially devitrified) (1, 5)
  - Trachyte (?) (1) (Thin section shows less than 5 per cent quartz which may be secondary.)
- Phanerites
  - Alaskite (3)
  - Aplite (4)
  - Diabase gabbro (1, 2, 5)
  - Diorite (1, 5)
  - Granite (pink, with myrmekitic intergrowths of orthoclase and quartz) (1, 2, 5)
  - Graphic granite (1)
  - Greisen (1, 2, 3, 4)
  - Nepheline syenite (?) (weathered) (1)
  - Serpentinized peridotite (?) (5)
  - Syenite porphyry (5)

Metamorphic rocks
- Garnet gneiss (1)
- Greenstone (1, 5)
- Hornblende-biotite gneiss (1, 2, 5, 8)
- Hornblende-quartz gneiss (5)
- Novaculite (pale cream-colored microquartzite) (1, 3, 4, 7, 8)
- Quartzite, arkosic (4)
- Quartzite, black (1, 3, 4, 6, 7)
- Quartzite, pink (Baraboo quartzite ?), (1, 2, 6, 7)
- Quartzite, white (very fine grained) (5, 7)
- Taconite (ferruginous chert) (1, 7)

Partial list of other rocks
- Coal, cannel and bituminous (1, 2)
- Silicified Favosites (2)
- Silicified Zaphrentis (1.5 inches in diameter) (1)

Granites, gneisses, and quartzites are the most abundant of all igneous and metamorphic rocks represented, regardless of size. Rhyolites are of nearly equal abundance with the granites in the larger sizes (4–12 inches), but not so many were found in the smaller sizes. Diabase-gabbro was found only in the larger sizes whereas the basalts are present only as pebbles. Neither rock type was abundant at any locality. Only two samples each of syenite porphyry and diorite were found.

Rocks of these general types have only been reported from one other locality in Louisiana, the Chandeleur Islands in St. Bernard Parish (2).

Possible Source Regions.—The Lake Superior Upland and the igneous areas of the Central Interior region appear to be the only source areas of these rock types. A number of rock types are common to both regions and it is doubtful if more than two or three specimens can be definitely referred to either one. They may, however, be roughly divided into two groups corresponding to the two regions. The Central Interior areas are chiefly igneous, the Lake Superior region predominantly metamorphic. Hence the presence of one or two distinctive rock types in each group may be considered indicative of the group as a whole.

Several of the individual rock types and a general suite of acid igneous rocks suggest possible derivation from the closely allied petrographic regions of the Central Interior, the St. Francis, Arbuckle, and Wichita mountains. Devitrified rhyolite (aporhyolite) has been described from each of these mountain areas. The samples collected consist of resorbed and corroded phenocrysts of quartz and orthoclase imbedded in a spherulitic groundmass of devitrified glass. Thin sections of some specimens indicate almost complete devitrification of a glassy base to a finely divided quartzose groundmass.

The granite porphyries collected are without exception pink to brick-red in color and, megascopically, are apparently coarsely crystalline. Microscopic examination, however, shows their finely granular groundmass texture and their true porphyritic character. The porphyries are characterized by myrmekitic intergrowths of quartz and feldspar and by a very small percentage of hornblende, or biotite, or both.

One specimen of quartz monzonite was

found. It seems to be closely allied to the granite porphyries but contains about 20 per cent oligoclase feldspar. Myrmekitic intergrowths of quartz and orthoclase are present but comparatively scarce.

Other rocks which may have had their source in the Central Interior igneous areas are those of diabase-gabbro, diorite, aplite, micropegmatite, graphic granite, and quartzite. The rock tentatively identified as nepheline syenite may have come from the alkalic Magnet Cove, Ark., area or adjacent alkalic rock areas. Novaculite (pale cream-colored microquartzite), which is common in many exposures in central Louisiana, undoubtedly came from these areas also.

Characteristic of the Lake Superior upland of the pre-Cambrian shield are two rock types of the collection, amygdaloidal basalt and taconite. The basalt, with original vesicles filled with quartz, calcite, and a zeolite (natrolite ?), is typical of dense red Keweenawan lavas. The lath-like plagioclase phenocrysts of the specimen have been badly sericitized, but the basalt is otherwise remarkably free from weathering and so strikingly resembles the typical Keweenawan lavas that there seems to be little doubt of its source.

The taconite specimens appear to be particularly distinctive of the iron-bearing rocks of the Lake Superior region. They contain finely divided granules of iron oxide imbedded in a cherty groundmass. Some of the granules are massive but others show a microscopic banding of hematite about concretionary centers.

A group of basic igneous rocks, the diabase-gabbro, serpentinized peridotite (?), and diorite, could have been derived from this region, but they can also be found at present in the Central Interior igneous areas.

Several specimens of pink and red quartzite and a metamorphosed rhyolite are similar to rock types exposed in the Baraboo District, Wis. These rocks, as well as most of the rocks in the metamorphic group (quartzites, gneisses, schists, and greenstones) could have come from the northern pre-Cambrian areas. The only other possible source regions are the Rocky Mountains and the Appalachian Mountains. Since the other rocks seem to be distinctive of the northern area, and it is known that such rocks were carried far to the south as glacial drift, it seems more logical to assume that these materials had their ultimate source to the north and were reworked from glacial drift sheets in the upper Mississippi Basin.

CONDITIONS OF FLUVIATILE DEPOSITION

The changing conditions of fluviatile deposition are well shown in the varying lithologic and structural characteristics of the terrace deposits. The gradation from coarse lenticular basal deposits to more widespread and better sorted finer sediment at the top of each sequence indicates a change in stream type from overloaded, anastomosing, constantly flooding streams to single-channel, seasonally flooding ones. The change in type of stream, and in the grain size of the sediment deposited, definitely denotes a decrease in the supply of materials, or in the ability of the streams to carry their load. Greater carrying capacity during earlier stages of deposition could have been effected by an increase in the gradient of the stream, by an increase in available materials for transportation, or by a combination of both factors.

There is little to support the suggestion that the larger gravels were carried by streams with greater volume of water than that of present-day streams. It is possible that more water was carried by melt-water streams during and immediately after maximum stand of the glaciers than during the later stage glacial retreat. This is a questionable assumption at best, however, because ice advance and retreat were probably very gradual, and the amount of melting at the glacier's front should have varied

but little whether that front was advancing or retreating. Furthermore, the gravels derived from non-glaciated areas are comparable in size to those derived from glaciated regions, indicating that the carrying capacity of melt-water streams was no greater than that of streams from non-glaciated areas. This in itself casts doubt on any assumption of increased volume owing to melt-water from the glaciers.

Another little known factor, the relative size of drainage basins, must also be considered in connection with volume fluctuation. Both the beheading of drainage systems by glacial advance and the development of new systems with glacial retreat present serious obstacles to an appeal for great volume of water. It is quite possible that the volume of run-off during interglacial stages would be greater because the drainage basins would be larger after ice retreat.

On the other hand, there can be little question concerning a great increase in gradient of streams during glacial stages. The thesis that sea level was lowered by the accumulation of ice on land has been proved through various lines of reasoning and from geologic evidence in many parts of the world. Lowering of sea level in the Gulf of Mexico region caused the entrenchment of the Pleistocene Mississippi River system. Using the modern Mississippi River as an example, it can be shown that the entrenchment was accomplished without greatly increasing the length of the stream. Lowering of the present Gulf by 300 feet, accepted maximum effect of glacial accumulation, would increase the length of the Mississippi by 100 miles at a maximum. Possible straightening of the channel during entrenchment might even decrease its length. Glacial blanketing of the stream headwaters would also tend to shorten the stream. Hence a 300-foot entrenchment of the streams would cause an enormous increase in gradient and consequent carrying capacity.

In summary, the Quaternary history of the Gulf Coast appears to be as follows. A long period of equilibrium between weathering and transportation existed in the central drainage basin during Tertiary time. This is indicated by the similarity in character of the Tertiary deposits. Entrenchment of streams during the first glacial stage destroyed this equilibrium. The development of steep lateral tributaries accompanied headward main-stream entrenchment and provided the necessary agents for removal of the deeply weathered regional debris. Streams like the Mississippi which drained glacial fronts were also furnished great quantities of glacial drift. As a consequence, the main streams were overloaded with enormous quantities of sediment derived from tributaries all along their courses. Streams entrenched during later stages of glaciation also received materials from the weathered Tertiary mantle and glacial drift but much of the coarse deposits of the later alluvial stages was reworked from earlier Pleistocene terrace deposits.

The initiation of each deglaciation stage halted the process of stream entrenchment. As the oceanic basins were gradually replenished the base level of streams was raised. Thus the steep-gradient streams of maximum glaciation slowly lost velocity and carrying capacity. Deposited materials became finer and finer as the glacial valleys were alluviated.

Hence each depositional sequence represents the alluviation of valleys cut by glacial streams with steep gradients. The regularity of the alluvial sequence, whether exposed along main streams or in small tributaries, denotes a gradual decrease in stream gradients.

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SORTING AND TRANSPORTATION OF MATERIAL IN THE SWASH AND BACKWASH

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ABSTRACT

The great variation in velocity of the moving water in the swash and backwash causes extensive sorting of the beach material. As a result there are considerable differences in the rate at which beach sediments of various sizes are transported.

Mechanical analyses were made of the beach sands to show the amount and character of the sorting. Also the behavior of suspended sediments in the swash and backwash were observed to determine the peculiarities of transportation.

The conclusion is reached that it is the sediments of medium size that are transported most rapidly by beach drifting.

When waves meet the shoreline at an acute angle a part of the loose material of the beach is transported to leeward along a somewhat zig-zag path under the action of the swash and backwash. The amount of sediment moved in this way is not so great as that transported along the subaqueous terrace by the waves and currents yet it is considerable and an important factor in the building of structures such as spits, bars and barriers. For this phase of transportation of shore materials Johnson has proposed the term "beach drifting" to distinguish it "from the longshore transportation effected by the currents in the water just outside the beach."

An incoming oscillation wave as it moves toward the shore changes to a wave of translation and advances up the beach slope. As the swash of the wave ascends the sloping beach more and more of its energy is lost and thus the velocity of the advancing water gradually decreases until it becomes zero. It is evident that the energy of the swash has its source in the energy of the incoming wave, but that the velocity of the backwash as the water flows back down the slope is owing entirely to gravity as it starts from a state of rest and moves faster and faster until it reaches the plunge line. As has been pointed out by Johnson, the velocity of the returning water is generally less than that in the swash and is "really an hydraulic current containing no element of true wave motion." This loss of velocity is partly the result of friction which acts on both the ascending and descending water and partly because the volume of the returning water is less since some of it is absorbed by the sediments over which it is moving. It is also evident that the less the slope of the beach the greater will be the difference between the velocity of the swash and the backwash.

A result of this variation in velocity is much sorting of the sediment as it is moved about on the beach slope. As is well known, the sorting of sediment by moving water results in a segregation of the various sizes. The smaller materials accumulate in the slower moving water and the larger materials in the swifter. Accordingly in the beach slope the finer sediments should be found near the swash line where the water is stationary, or nearly so, and the coarser at the plunge line where it has its greatest velocity.

In order to test, if possible, the amount of sorting of sediments in the beach, samples were taken at the plunge line, at the upper edge of the swash and at a median line between the two. They were collected from a representative sandy beach on the east shore of Lake Michigan covering a distance of about a mile on each side of the entrance of White Lake

Harbor. To insure that the samples should be as nearly representative of the three positions in the swash as possible they were collected, a spoonful at a time, from different places along the beach and at different times. Also care was taken to collect only after steady winds had been blowing for several hours so as to insure a complete sorting of the surface sands of the beach.

Each sample, containing about one quart of sand, was then thoroughly dried and mixed. They were then analyzed by placing 250 grams in a sieve nest in the mechanical sorter in the laboratory of the Oklahoma Geological Survey and agitating for 20 minutes.

Plunge line sample.
Two hundred fifty grams.

	Grams
Retained on 0.840 mm. screen	2.310
Retained on 0.701 mm. screen	2.820
Retained on 0.589 mm. screen	10.890
Retained on 0.417 mm. screen	127.460
Retained on 0.295 mm. screen	94.765
Retained on 0.208 mm. screen	12.445
Retained on 0.147 mm. screen	.185
Retained on 0.104 mm. screen	Trace
Total	250.875

Median line sample.
Two hundred fifty grams.

	Grams
Retained on 0.840 mm. screen	1.000
Retained on 0.701 mm. screen	1.555
Retained on 0.589 mm. screen	5.755
Retained on 0.417 mm. screen	103.475
Retained on 0.295 mm. screen	121.760
Retained on 0.208 mm. screen	16.330
Retained on 0.147 mm. screen	.150
Retained on 0.104 mm. screen	.015
Retained on pan	Trace
Total	250.040

Swash line sample.
Two hundred fifty grams.

	Grams
Retained on 0.840 mm. screen	.095
Retained on 0.701 mm. screen	.235
Retained on 0.589 mm. screen	1.475
Retained on 0.417 mm. screen	66.115
Retained on 0.295 mm. screen	148.657
Retained on 0.208 mm. screen	33.265
Retained on 0.147 mm. screen	.835
Retained on 0.104 mm. screen	.085
Retained on pan	.025
Total	250.787

An examination of the above figures shows that the waves produce a decided sorting action in the beach sands. The coarsest material is found in the swiftest water near the plunge line and the finest near the upper limit reached by the waves.

The dividing line between the smaller and larger sediments is between 0.295 mm. and 0.417 mm. The sand grains larger than 0.417 mm. in diameter are present in decreasing amount with distance from the water's edge, while those smaller than 0.417 mm. are present in increasing quantities. The only exception to the gradual decrease of finer sediment with distance from the water line is in those materials retained on the 0.147 mm. screen. Here there is a slight falling off from the plunge line to the median line and then a great increase at the swash line. The explanation of this is found in the black sands which contain considerable quantities of magnetite and are quite common in the beach. At the plunge line and the median line the finer sediments contained little or no magnetite while the upper line sediments retained on the 0.147 mm. and 0.104 mm. screens were mostly magnetite. However that which passed through the 0.104 mm. screen from the upper line was mostly silica with little magnetite.

Thin layers of black sands containing a high percentage of magnetite are quite commonly found in the beach sands of the eastern shore of Lake Michigan. The segregation of these sands by the waves and currents takes place mostly in the upper part of the swash. The controlling factors in this segregation are their fineness and high specific gravity.

A mechanical analysis of a sample of

the black sand containing 147 grams gave the following results.

	Grams
Retained on 0.351 mm. screen	0.980
Retained on 0.295 mm. screen	0.975
Retained on 0.246 mm. screen	1.360
Retained on 0.208 mm. screen	15.380
Retained on 0.147 mm. screen	88.545
Retained on 0.104 mm. screen	38.225
Retained on pan	1.655
Total	147.120

This shows that 128.425 grams out of 147.120 grams of the black sand, or over 87 per cent is smaller than 0.208 mm. in diameter. Hence so far as its sorting is controlled by size it should be deposited near the upper limit of the swash. This is apparently the case to a great extent in spite of its greater specific gravity which is nearly double that of quartz.

Since the swash line is not always at the same height on the beach because of the difference in the energy and height of the waves it follows that some of the finer material is stationary part of the time and that some of the remainder moves only slowly because of the low velocity of the water as it stops and begins its return down the slope. Again at the plunge line some of the coarser material is returned to the lake bottom and is no longer a part of the beach ridge while a part of the remaining coarse material is moved only slowly. From these considerations it is apparent that the material which travels most rapidly along the beach is that near the median line.

In an attempt to test the relative rate of travel of sediments of various sizes observation was made of the rate of movement in the swash and backwash of various types of suspended materials. In the first test wooden balls of different sizes but the same density were placed in the swash and their relative rates of travel observed. In order to eliminate as far as possible the effects of local irregularities of beach and wind straight reaches of shoreline about 1,000 feet in length were selected and three sets of observations made on different days and under different wind conditions.

In the first experiments two wooden balls having diameters of $3\frac{1}{2}''$ and $1\frac{3}{4}''$ respectively were used. A total of eleven trials was made. In every trial the larger ball finished the course considerably ahead of the smaller although in some trials the smaller ball was ahead part of the time. When this happened it was usually during its passage over the first part of the course.

In watching the two balls it was quite evident that there are two causes responsible for the faster travel of the larger ball. The small ball being lighter and of smaller diameter was carried higher by the swash and so was thrown somewhat ahead of the larger one in its upward journey but the return trip in the backwash took longer because of the slow current near the swash line and also because whenever the balls were in contact with the beach surface the smaller ball rolled more slowly down the slope because of its smaller diameter. Thus in its return trip the small ball lost more than it gained by being thrown ahead of the large ball in the upward movement. Again the smaller ball because of its lesser diameter and hence its lesser weight in comparison with its surface was thrown higher on the beach and so was lodged above the swash line more frequently and for longer periods of time than was the larger ball. Of the two the latter is perhaps the more important factor.

In the second series of experiments two floating rubber balls were used, each two and five-eights inches in diameter. One weighed 86 grams, the other 60 grams. In a series of seven trials performed in the same manner as those described above the heavy ball always finished the course ahead of the other and for the same reasons.

It was next attempted to study the rate of transportation of submerged material in the swash by using spheres cut from coal of from one-half inch to one

and one-half inches in diameter. This did not prove very successful because notwithstanding the low specific gravity of the coal the spheres after making one or two trips in the swash went down through the plunge line and joined the layer of gravel on the lake bottom below the water's edge.

An attempt was also made to measure the relative rate of beach drifting by laying a line of powdered coal on the beach from the plunge line to the swash line and observing its rate and manner of drift. Repeated trials indicated a falling behind of the finer material at the swash line and also a lag of the coarse material at the plunge line; the whole forming a rough crescent convex to leeward. While the material could not be traced very far because of the rapidity with which it mingled with the beach sands, the test indicated that it is the materials along the median line that are transported the most rapidly along the beach.

From the above analyses and observations it seems certain that the finest sediments thrown high on the beach by the waves travel more slowly than the coarser ones which are kept more constantly in movement, and that some of the finest material is thrown high on the beach where it remains stationary for considerable periods of time. Also at least a part of the coarser materials lag behind in their journey. Hence the greatest amount of movement and consequently the greatest grinding action in the beach sands of the area studied takes place in those sediments ranging in size between 0.25 mm. and 0.60 mm. Of course some of the finer materials escape seaward in the same swift water that carries the coarsest material out beyond the plunge line.

Johnson[1] has made an analysis of the travel of materials by beach drifting in which he reaches the conclusion that the smaller particles travel the faster because they are thrown higher on the beach and thus are carried farther to leeward in the parabolic path they follow. From the above it can be seen that this can only be true for such particles as remain continuously in suspension in the swash and backwash during the complete period of a forward and backward movement.

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VARVE-LIKE DEPOSIT IN A SOLUTION CHANNEL

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ABSTRACT

An old solution channel in the Burlington limestone near Columbia, Missouri, was found to be filled with a silt and clay deposit which, because of its laminated structure, resembles a varved clay. Closer study, followed by experimental deposition of material from the deposit in the laboratory, pointed to the conclusion that it is only varve-like. The control of alternation in sediment was probably a fluctuating ground water supply, not seasonal temperature variation.

Solution channels are common in a limestone region and even those partly or completely filled are ordinarily not significant, but one seen by the writer which contained a deposit made up of laminae resembling varves seemed sufficiently interesting to be worthy of description. Although the Kansan ice sheet extended south into the region yet the unusual occurrence of the varve-like fill cast doubt as to its dependence upon glacial origin. If the laminae are typical varves (assuming typical varves are developed as sedimentary deposits from seasonal melting of glacial ice) their occurrence is unique and the process of their formation within a cave so unusual that it was not visualized at first sight. On the other hand, if the cause for this rhythmic deposition is not logically that for conventional varves then additional means for repeated cyclic variation in sedimentation which might even be applied elsewhere must be considered. In either case the occurrence is thought provoking.

The location of the deposit under discussion is in Fellow's Quarry, about one-half mile south of the city limits of Columbia, Missouri. The country rock is the abundantly fossiliferous, crinoidal Burlington (Mississippian) limestone. The Burlington is a rather pure calcite limestone except for abundant large chert nodules. Solution work, both of Recent and pre-Pennsylvanian times, is prominent in this formation; not only are caves and sink-holes developed on today's landscape but ancient ones filled with Pennsylvanian sediments are exposed occasionally in road cuts or quarry faces. The filling materials (Pennsylvanian) are usually sandy shales with more or less chert or sandy fire clays which commonly show evidences of slumping during or subsequent to deposition, but are not "varved" like the one in question.

The particular cave or channel fill to be described was bared by driving back a quarry face which was abandoned at that place after clearing away the limestone shot down when the channel was exposed. In the visible cross section it is roughly triangular in shape with the base of the triangle above. The altitude of the triangle is about eight feet, and the base is about eighteen feet long. A small channel leads up about two feet from the roof of the main channel to connect with another small cavity roughly two feet high and parallel to but slightly shorter than the top of the larger one. The floor, walls, and ceiling of the cavities are irregular because of inward projecting limestone masses and jutting chert nodules. Except for the filling, the cave is like many others of the region.

Both parts of the solution channel are now continuously and completely filled by a clay and silt deposit which,

except for marginal contacts, is horizontally laminated in units up to six millimeters thick (averaging 2 mm.). Laminae are colored alternately light and dark gray. The deposit is fairly well indurated and breaks with conchoidal fracture, usually more readily across laminations than along them, resembling in its talus slope an outcrop of flint fire clay.

The laminae can usually be traced by color across the whole face of the deposit and only at the walls or against a projecting tongue or rock are they curved, broken, or taper out. At these margins, however, settling and movement after deposition may have bent or faulted and sometimes crushed the laminae to obliteration. Where deposition took place against projections from the wall two contact relationships were seen. Where the face of the projection is a vertical plane the laminae end abruptly against it like siding on a house wall against a window casing. Where the projection is lenticular in cross section (as a chert nodule) the laminae above and below the lens mid-section taper and curve up and down respectively, similar to the relations of bedding to syngenetic concretions.

These relationships suggest that settling and compaction of each layer had well advanced before there was influx of additional sediment. Certainly tapered arching of laminae over chert lenses would not have occurred with continuous dumping from suspension. Arching due to differential compaction would produce tension cracks over crests but none was observed. Wedging out of laminae beneath a lens was developed because less mud settled under the protecting roof of the lens than outside it. Curving of the wedge ends occurred as succeeding suspensions filled the gaps between earlier laminae and the chert lenses after they (earlier laminae) were compacted. The writer believes that discontinuous sedimentation as just described is in accord with other factors of origin to be discussed later.

DESCRIPTION AND MINERALOGY OF THE LAMINAE

A close study of a number of laminae under binocular and petrographic microscopes shows them to be composed chiefly of clay, but averaging also in estimated content about 10 per cent quartz and 20 per cent calcium carbonate in silt size. These proportions vary widely from lamina to lamina.

Commonly the lower three-fourths to seven-eighths of a lamina consists of relatively coarse grains or flakes .03 mm. to .08 mm. in diameter which are mixed and bonded with a minor amount of very fine clay particles. These coarser grains, which are quartz, calcite, and clay aggregates, are most abundant at the bottom of the lamina. Usually, but not always, black organic matter, present either as coarse particles or as a coating on coarse particles, is also most prominent in the lower part, darkening it appreciably. As one moves up in a lamina section usually the dark-colored organic matter decreases, and the ratio of fine particles (clay mineral particles) to silt increases with the result that the upper fourth to eighth part of a lamina appears finer-grained than the lower. This is to be expected where settling out of a suspended load is complete.

Generalization on color in laminae, however, is less positive. The top fine clay fraction may vary between being white, largely white with a very fine black strip at the very top, or the upper half of it may be quite dark, almost black.

The clay mineral is of the highly birefringent group, i.e., beidellite, or perhaps the potash bearing (illite?) group, and not kaolinite. The clay flakes show a high degree of parallel orientation where they are the chief constituents of the rock, alternately lighting and extinguishing when viewed between crossed nicols. A mineralogical study shows that the variation in grain size of a lamina from coarse to fine is fairly closely coincident and dependent upon the decrease

of quartz and calcite (coarse particles) and increase of clay mineral, that is, a gradual change in mineral species instead of a decrease in grain size of a more or less uniform mineral mixture. Probably the very finest fraction of the clay is an accumulation of colloidal floccules. Occasionally a very coarse grain of limestone or particle of chert, of the order of 2 mm. in diameter, is embedded within a lamina or across a pair of them. These grains resemble those standing out in relief from the solution etched walls and ceiling of present day caves in the Burlington limestone and no doubt are merely such grains which became detached and fell into the soft mud during accumulation.

The contact between laminae, or more specifically the change from the upper fine-grained part of a subjacent lamina to the coarse lower part of the one above is quite abrupt, and occurs along a surface which is rather smooth, sometimes gently undulatory, and occasionally indented by one or more of the coarser grains from above. This relationship adds evidence to the belief that settling of one influx of sediment was essentially complete before the arrival of another.

ORIGIN OF THE DEPOSIT

The writer while giving consideration to several possible mechanisms of deposition set up a small (9" diameter, cylinder) transparent sedimentation tank in which a laboratory deposit similar to the natural one might be reproduced. A supply of the natural laminated clay was air and water slaked, and then well blunged (with a little sodium carbonate added as deflocculant) to a muddy water suspension before being run into the sedimentation tank for settling. After settling was essentially complete another suspension was introduced in proper quantity that the layer formed after partial compaction was of the same order of thickness of those in the natural fill. Hence conditions of deposition of the original were duplicated as near as possible.

It was found that the new sand, silt, and clay suspension could be introduced quietly enough not to erode the previous layer only when considerable still water covered the previous deposit. One would infer from this that the quarry channel deposit was formed under relatively standing water conditions and that sediment for each layer was introduced with a negligible amount of turbulence.

As has been noted, each layer or lamina of the fill is surprisingly uniform in thickness throughout its area. This must mean that the mud was uniformly suspended in the water from which it settled. Such uniformity of mixing could not occur in a 2 or 3 inch deep pool without sufficient current action to develop "diastems" in older laminae.

These conditions point toward the supposition that the old solution channel was filled almost or completely to the top (completely at least toward the last of the fill) with quiet or very slowly moving water and that fine sand, silt, and clay was introduced through openings from above. These openings must have connected with another channel or a sinkhole from which fine sediment fractions only were delivered. Either the sediment settled in from its place or origin above, or came in as a mud-heavy water which displaced clear water lighter in weight.

The varve-like appearance of the deposit indicates rhythmic sedimentation and if the concept of conventional varves is followed would suggest annual layers. A good test of the applicability of this explanation would be a favorable comparison of the writer's material with true varved clays. An opportunity to make this comparison was accorded the writer by Professor W. A. Tarr who permitted study of varved clay collected from the Champlain formation of the Connecticut valley.

Examination showed the Champlain varves to be made of thicker laminae, to contain less clay "paste" (colloidal

clay), and to be far richer in white mica than the local sediment. Mechanically disintegrated material predominates in the glacial lake varves but chemically weathered minerals are more abundant in the cave deposit. Clean splitting frequently occurs along the weakly-cemented, parallel-oriented mica flakes in the coarser bands of the varves whereas conchoidal fracture across laminations prevail in the Missouri rock. Obviously there are very clear cut mineralogical differences between the two sediments and inferentially different sources of material and mechanisms of deposition. These are adequate, the writer believes, to rule out the laminated channel fill from a true varved deposit.

The difference in fracture, no doubt, is due also to the difference in mineral content, i.e., an abundance of homogeneously bonding colloidal clay and silt in the writer's material but a sparseness of cement with the overlapping mica plates in the varves. The source of the clay and quartz silt in the cave fill is logically the insoluble residue left from weathered limestone like the present enclosing rock. Whether the residue was left during solution in Paleozoic or recent times is not positively determinable, but association with other Pennsylvanian fills suggests a Paleozoic age for it.

The question as to whether the sets of laminae represent annual accumulations or whether they should be correlated rather with shorter-interval changes in ground water supply has not been determined because of limited evidence. Perhaps the only bit of evidence which may bear on the origin is the variation in color in the laminae with particle size, an argument against annual deposition. Because of this weak reason, or perhaps because of a first impression the writer favors a correlation of the laminae with rainy spells and/or melting snows rather than strictly annual changes. This support to the earlier mineralogical evidence against the channel fill being a true varved clay adds to the reason for calling it a varve-like deposit.

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 9, NO. 1, PP. 36–41, FIGS. 1–2, TABLES I–IV, APRIL, 1939

TYPES AND SOURCES OF SEDIMENTS DEPOSITED BY THE SOUTH CANADIAN RIVER IN NEW MEXICO AND TEXAS

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ABSTRACT

The heavy minerals deposited by the South Canadian River are magnetite, ilmenite, garnet, epidote, rose, pink, green, and black tourmaline, hematite, and purple, transparent, and brown zircon. These minerals are present in the river deposits throughout New Mexico and Texas, but decrease in abundance downstream as far as the Amarillo region. Below Amarillo magnetite, epidote, ilmenite, garnet, rose tourmaline, and hematite increase. Boulders are composed of granite, basalt, and sandstone. They are large, abundant, and angular near the source of the stream, but are absent in the eastern part of the Texas Panhandle. Tributaries flowing across basaltic lava flows carry an abundance of tourmaline; however, this mineral is of minor importance when the sediments are derived from granites. Other tributaries that secure their sediments from Triassic and Tertiary sedimentary rocks deposit the same heavy minerals as the river.

The South Canadian River has its source on the eastern slope of the Sangre de Cristo Mountains in north central New Mexico. From its source the river flows southward, paralleling the mountain range to the vicinity of Tucumcari, New Mexico, where it swings eastward through the plains of eastern New Mexico and the Panhandle of Texas. The chief tributaries in New Mexico are the Cimarron River, Mora River, Ocate Creek, Ute Creek, and Tucumcari Creek. In Texas some of the important tributaries include West Amarillo Creek, Antelope Creek, and Red Deer Creek. Cimarron River, Mora River, and Ocate Creek have their sources on outcropping intrusives of the Sangre de Cristo Mountains. The other tributaries are located on the plains and flow from sedimentary outcrops.

COLLECTION AND PREPARATION OF MINERALS

Sand samples were collected from the South Canadian River and the above-mentioned tributaries. River samples in New Mexico were secured near the towns of Taylor Springs and Logan, and from the Red River Canyon about 10 miles west of the town of Roy. Samples were collected in Texas near the towns of Amarillo, Borger, and Canadian. Samples from the tributaries were secured near their junction with the river. The samples collected at each locality represent a cross section of the stream deposits. In the laboratory 20 grams of each sample were sieved to secure the representative grades. From each grade the heavy minerals were removed, identified, and counted. The quartz grains were classified according to amount of abrasion, as rounded, sub-rounded, sub-angular, and angular.

Pebbles ranging in size from 1 to 5 cm. were collected and arranged in different sizes as follows: diameters 3 to 5 cm., 2 to 3 cm., and 1 to 2 cm. The amount of abrasion was determined by the shapometer.[1] The type and shape of the boulders larger than 5 cm. were noted.

RIVER SEDIMENTS IN NEW MEXICO

About 10 miles west of the town of Roy, New Mexico, the South Canadian River has cut a canyon, locally known as the Red River Canyon, several hundred feet deep in the Cretaceous sandstones. The sediments within the Red River Canyon are used as a type, with which deposits in other areas are compared. In this canyon the channel is

narrow with alternating deeps and shoals. The sediment range is from fine sand to boulders. Generally, the fine materials are associated with the deeps, and the coarse with the shoals. The light-weight minerals consist primarily of quartz and dark colored calcareous particles. The heavy minerals are magnetite, ilmenite, garnet, epidote, rose, pink, green, and black tourmaline, hematite, and transparent, brown, and purple zircon. The abundance of the heavy minerals, according to size, is shown in Table I. At low water stage the sand transported in the river channel has a maximum diameter of $\frac{1}{4}$ to $\frac{1}{8}$ mm. Quartz grains 1 to $\frac{1}{2}$ mm. in diameter show the greatest amount of abrasion. The per cent of angularity of the quartz grains increases with the smaller sizes.

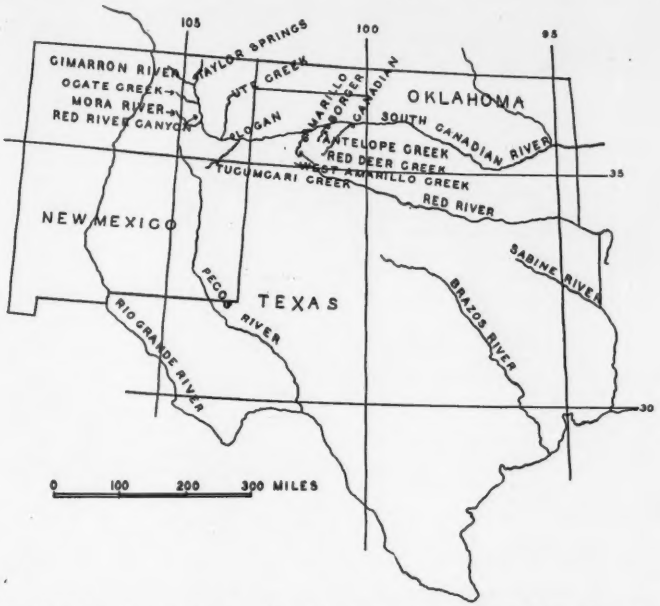

FIG. 1.—Map showing the location of South Canadian River and its tributaries.

TABLE I.—*Abundance of heavy minerals in Red River Canyon. Per cent of total for each grade*

		Millimeters				
		1–½	½–¼	¼–⅛	⅛–1/16	1/16–1/32
Magnetite		—	8	4	12	18
Ilmenite		37	22	14	31	37
Garnet		—	3	6	5	2
Epidote		13	3	16	15	3
Tourmaline	Rose	—	1	6	4	3
	Pink	—	1	10	6	5
	Green	13	15	16	6	2
	Black	—	2	2	1	2
Hematite		37	43	23	12	5
Zircon	Trans.	—	1	1	4	11
	Brown	—	—	1	1	2
	Purple	—	1	1	3	10

Most of the boulders and pebbles were deposited in the shoals and on the concave sides of meanders. They are composed of quartz, granite, basalt, and sandstone. The percentage of abrasion on the pebbles is as follows: diameters, 3 to 5 cm. 65, 2 to 3 cm. 56, and 1 to 2

cm. 49. The largest boulders, 2 to 3 feet in diameter, are sandstone. They are angular and of local origin. The diameter

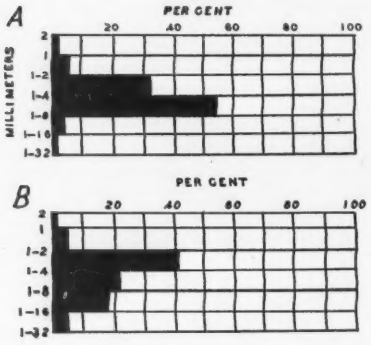

FIG. 2.—Graphs showing the texture of the sand (*A*) transported in the river channel, Red River Canyon; (*B*) deposited in the river channel at Amarillo.

range of the granitic and basaltic boulders is from 3 to 14 inches, average about 10 inches. The majority of these boulders are sub-angular.

TABLE II.—*Percentage of abrasion on the quartz grains, Red River Canyon*

	Millimeters			
	1–½	½–¼	¼–⅛	⅛–1/16
Rounded	16	10	—	—
Sub-rounded	23	19	17	9
Sub-angular	28	28	33	20
Angular	33	43	50	71

At Taylor Springs, about 30 miles upstream from Roy, New Mexico, the river sediments contain the same heavy minerals as shown in Table I. The decrease in abundance of these heavy minerals, as compared to Red River Canyon, is more than 50 per cent. The sand deposits in the river channel have a coarser texture than in Red River Canyon and the maximum size grade is ½ to ¼ mm. in diameter. The boulders are small and consist chiefly of hard shale fragments. The sediments in the river and tributaries above Taylor Springs are derived chiefly from Tertiary and upper Cretaceous sedimentary rocks, but a few small dikes are responsible for a small quantity.

The variation in the sediments of the South Canadian River at Red River Canyon and Taylor Springs is due in part to the materials transported by two tributaries, Cimarron River and Ocate Creek. Another reason is the absence of deeps at Taylor Springs. Cimarron River secures practically all its materials from granites and other intrusives, chiefly porphyries. The sands are coarse, angular, and contain all the heavy minerals found in Red River Canyon with the exception of green, pink, and black tourmaline. The boulders are large, and are composed of quartz, basalt, and granite. Practically all the sediments in Ocate Creek are derived from a basaltic lava flow. The deposits consist of coarse sands, and basaltic pebbles and boulders. The heavy minerals include an abundance of green and pink tourmaline, and minor amounts of magnetite, ilmenite, epidote, black tourmaline, and hematite. The tributaries secure and transport all the heavy minerals that are concentrated in the deeps of Red River Canyon.

From Red River Canyon to Logan, New Mexico, a distance of about 50 miles, the river flows on Triassic sediments and in the vicinity of Logan the river has cut a deep canyon in Triassic sandstones. Here the sand deposits in the channel have a maximum size grade, 65 per cent, ¼ to ⅛ mm. in diameter, as compared to 54 per cent for sand with the same diameter in Red River Canyon. The decrease is more than 40 per cent for all the heavy minerals except magnetite, ilmenite, and brown zircon, which increase 9, 6, and 15 per cent, respectively. The general decrease in the abundance of heavy minerals at Logan is probably due to the absence of deeps in the river channel. The per cent of rounded quartz grains for the size 1 to ½ mm. in diameter is 20, as compared to 16 in Red River

Canyon. All the boulders except those composed of sandstone are small and rounded. The sandstone boulders are large and local.

Some of the important tributaries between Red River Canyon and Logan are Mora River, Ute Creek, and Tucumcari Creek. Mora River flows first from granites across Tertiary and Cretaceous sedimentary outcrops, then over a basaltic lava flow. The sediments in Mora River consist of coarse sands, pebbles, and boulders. The largest boulders are composed of granite and basalt. The abundant heavy mineral is black tourmaline, which is associated with minor amounts of magnetite, ilmenite, epidote, garnet, rose tourmaline, and hematite. The course of Ute Creek is from a basaltic lava flow over Cretaceous and Tertiary sedimentary rocks. It transports all the heavy minerals with approximately the same abundance as the river at Logan. Boulders and pebbles are angular and composed of quartz, basalt, and granite. Tucumcari Creek flows from Tertiary over Triassic outcrops. The sediments consist of sands, quartz pebbles, and sandstone boulders. The sands have a coarser texture than those in the main stream. As compared to the deposits in the main stream at Logan, heavy minerals increase in abundance with the exception of epidote, green and black tourmaline, and purple zircon.

RIVER DEPOSITS IN TEXAS AREA

The South Canadian River Valley in the Texas Panhandle has a width of about 20 miles from rim to rim, and the bed of the stream is about 550 feet below the level of the High Plains. The channel is crooked, broad, and braided. Tertiary, Triassic, and Permian rocks are exposed. The sediments in the river consist chiefly of sands, pebbles, and fragments of clay. The finer sediments are deposited near the main channel, but the coarser materials are usually at a higher level, or near the edge of the stream. The Santa Fe Railroad Company excavated into the bed of the stream for the piers which support the railway bridge about 18 miles north of Amarillo, and their section, secured from the Santa Fe office, Santa Fe Building, Amarillo, Texas, of the sediments for the east pier number 11 from the south end of the bridge is as follows:

5 ft. 5 in.—fine clay
3 ft. 6 in.—sand, gravel, and boulders
8 ft. 4 in.—sand and gravel
10 ft. 7 in.—coarse sand and gravel
14 ft. 4 in.—coarse sand, gravel, pieces of cap rock
17 ft. 4 in.—coarse sand and gravel
7 ft. 4 in.—fine sand, lumps of clay
15 ft. 2 in.—fine sand, gravel, sandy clay
7 ft. 0 in.—sand and sandy clay
20 ft. 1 in.—fine sand, gravel, pieces of cap rock
6 ft. 5 in.—fine sand with small amount of coarse sand and gravel

This section indicates that the bed of the stream was formerly more than 100 feet lower than at present. The alternating deposits of fine sand, coarse sand, and gravel are the result of a shifting channel.

In the Amarillo area the river transports all the heavy minerals found in the Red River Canyon, but there is a marked decrease in abundance except for brown zircon. The decrease for each of the heavy minerals, using the total number of grains, is; in per cent, magnetite 10, ilmenite 30, garnet 41, epidote 64, rose tourmaline 64, pink tourmaline 70, green tourmaline 85, black tourmaline 78, hematite 86, transparent zircon 36, and purple zircon 65. The minerals with the maximum decrease in abundance are those with a diameter of $\frac{1}{8}$ mm. or larger. The heavy minerals and their abundance in per cent of total number for each grade are shown in Table III. The maximum size grade of the sand deposits in the channel at the highway bridge has a diameter range from $\frac{1}{2}$ to $\frac{1}{4}$ mm. The coarse sands are carried into the river by tributaries which flow over Triassic and Tertiary sediments. About 25 per cent of

the quartz grains with a diameter range from 1 to ½ mm. are rounded. As compared with Red River Canyon, the per cent of increase of the rounded quartz grains, size 1 to ½ mm. in diameter, is from 16 to 25. The per cent of angular grains, diameter range ⅛ to $\frac{1}{16}$ mm., decrease from 71 to 50. In the Amarillo region the only sediments larger than sand are pebbles, clay fragments, and pieces of cap rock. The pebbles consist chiefly of quartz and the per cent of abrasion is: diameters, 3 to 5 cm. 71, 2 to 3 cm. 61, 1 to 2 cm. 52. Most of the clay fragments are transported to the river by tributaries from Triassic sediments. The shale fragments, locally referred to as clay balls, vary in diameter from ½ to 3 inches. They are irregular in shape, contain green colored circular inclusions, and exhibit stratification that is similar to the original shale outcrops. Evidently, these balls are pieces of shale that have been rounded by transportation.

TABLE III.—*Abundance of the heavy minerals in Amarillo area, per cent of the total of all the mineral grains in each grade*

		Millimeters				
		1–½	½–¼	¼–⅛	⅛–$\frac{1}{16}$	$\frac{1}{16}$–$\frac{1}{32}$
Magnetite		—	10	7	16	18
Ilmenite		50	21	25	37	55
Garnet		—	8	15	6	2
Epidote		16	20	21	11	2
Tourmaline	Rose	—	1	6	5	1
	Pink	—	3	7	5	2
	Green	—	8	7	2	1
	Black	—	—	1	1	1
Hematite		34	29	7	5	2
Zircon	Trans.	—	—	2	5	8
	Brown	—	—	1	3	4
	Purple	—	—	1	3	4

At Borger, about 35 miles below Amarillo, the river deposits all the heavy minerals found upstream, but there is a variation in abundance. As compared to the Amarillo region, the per cent of increase for magnetite is 36, ilmenite 39, epidote 58, garnet 35, rose tourmaline 57, hematite 52, and brown zircon 53. The per cent of decrease for pink tourmaline is 46, green tourmaline 44, transparent zircon 33, and purple zircon 18. The amount of black tourmaline does not change. This variation in the abundance of the heavy minerals corresponds to the material transported by the tributaries. The sand deposits in the river channel at Borger have a higher per cent of materials with a diameter range of ¼ to ⅛ mm. than at Amarillo. However, the maximum size grade is the same, ½ to ¼ mm. in diameter. The variations in the number of rounded quartz grains and the percentage of abrasion on the pebbles is slight.

The river deposits at Canadian, about 100 miles downstream from Amarillo, contain all the heavy minerals recorded in the Amarillo region. However, there is more than 100 per cent increase in the abundance of ilmenite, garnet, epidote, and rose tourmaline. The per cent of increase for magnetite, hematite, brown zircon, and purple zircon is 40, 35, 6, and 40, respectively. The per cent of decrease for pink tourmaline is 16, green tourmaline 56, black tourmaline 8, and transparent zircon 22. The maximum size grade of the channel sand deposits, 45 per cent, is ¼ to ⅛ mm. in diameter, which is a finer texture than the sand deposits at Amarillo. The pebbles are small, consist chiefly of quartz, and the per cent of abrasion for the following diameters is 3 to 5 cm. 74, 2 to 3 cm. 67, and 1 to 2 cm. 58. For corresponding diameters at Amarillo the per cent of abrasion is 71, 61, and 52.

In Texas some of the important river tributaries are West Amarillo Creek, Antelope Creek, and Red Deer Creek. The latter joins the river near the town of Canadian and all the sediments are derived from Tertiary deposits. In Red Deer Creek the abundance of heavy minerals closely corresponds to those in the Amarillo area except epidote which increases. In West Amarillo Creek both Triassic and Tertiary outcrops supply the materials. It transports the same heavy minerals as the river, but the

abundance of magnetite, ilmenite, garnet, epidote, rose tourmaline and hematite increases. Practically all the sediments in Antelope Creek come from Triassic outcrops and the heavy minerals except rose, green, and black tourmaline, as compared to the river deposits in the Amarillo area, show a substantial increase in abundance. Other sediments in the tributaries include: sands with a maximum size grade ½ to ¼ mm. in diameter, quartz pebbles, clay fragments, and pieces of caliche locally known as cap rock.

proximity of source rock. The source rock consists of basalt, granite, and prophyry intrusives, and Cretaceous and Tertiary sediments. The heavy minerals, as shown in Table IV, decrease in abundance downstream from Red River Canyon to Amarillo. Below Amarillo the abundance of magnetite, ilmenite, garnet, epidote, rose tourmaline, hematite, brown and purple zircon increases; the other minerals including pink and green tourmaline, and transparent zircon decreases. This increase and decrease in the abundance of the heavy minerals is di-

TABLE IV.—*The number of minerals counted from 20 grams of sand*

		Taylor Springs	Red River Canyon	Logan	Amarillo	Borger	Canadian
Magnetite		6	346	380	301	413	426
Ilmenite		40	923	980	598	822	1199
Garnet		14	185	85	103	140	266
Epidote		52	476	280	170	273	477
	Rose	48	152	83	56	88	144
Tourmaline	Pink	11	257	62	73	50	61
	Green	58	370	100	50	28	22
	Black	21	50	20	11	11	10
Hematite		145	653	142	85	127	117
	Trans.	24	128	55	82	55	64
Zircon	Brown	12	25	29	41	63	43
	Purple	40	110	37	38	31	55

SUMMARY

The variations of the sediments deposited by the South Canadian River are related to the rock outcrops from which the tributaries secure their sediments, to the number of tributaries, to the character of the stream bed, and to the distance from sources of sediments. Boulders near the source of the stream are large, abundant, and consist of granite, basalt, and sandstone. They become smaller and disappear downstream. Pebbles in the New Mexico area are abundant and consist of quartz, granite, and basalt, but in the Texas area they are absent except those composed of quartz. Heavy minerals are concentrated in the upper course of the stream due to the presence of deeps in the channel and rectly related to the sediments transported to the river by tributaries. Between Logan, New Mexico, and Amarillo the precipitation is light, thus number of tributaries is limited, and the sediments added to the river deposits are not sufficient to change the mineral content. In the vicinity of Amarillo and eastward the drainage system is better developed than to the west, therefore the gain and loss in the mineral content corresponds to the sediments deposited by the tributaries. The texture of the sand deposits in the river channel is coarser in the Amarillo area, than the sand near the source of the stream or in the eastern portion of the Panhandle. The variation in texture is due to coarse sands secured from Tertiary and Triassic exposures.

REFERENCE

[1]TESTER, ALLEN C., *1931*, The measurement of the shapes of rock particles: *Journal of Sedimentary Petrology*, 1, 3–11.

Manual of sedimentary petrography. By W. C. Krumbein and F. J. Pettijohn. xiv plus 549 pp., 265 figs., 53 tables. D. Appleton-Century Company, New York, (1938). Price $6.50.

This book is a comprehensive treatise on the methods of petrographic analysis of sediments with particular emphasis placed upon the mechanical and statistical phases. The authors state that the various techniques described from field sampling to the final graphic and statistical analysis have as their common aim the determination of the physical conditions of deposition of a sediment, the age of the deposit, and the determination of the provenance. The first half of the book, on mechanical analysis, was written by Krumbein and the second part, on mineral and chemical analysis, by Pettijohn.

Various methods of sampling, handling, and preparation of samples for analysis, such as splitting, mechanical and chemical disaggregation and dispersion are adequately described. The concept, function, and choice of a proper grade scale are discussed at length and the principles, and methods of mechanical analysis as well as graphic presentation and statistical analysis of the data are outlined in great detail. A discussion of the recent developments in the technique of orientation analysis of sedimentary particles concludes the section on mechanical analysis.

The second part of the book is introduced by a discussion on the importance of quantitative and statistical methods in studying the shape, degree of roundness, and type of surface texture of sedimentary particles. The technique involved in the preparation of the sample, separation of the heavy minerals, and the mounting of the heavy mineral fraction for microscopic study is treated with less thoroughness than might be expected. The practical optical methods of mineral identification are briefly summarized. The authors are to be congratulated on the fact that they have omitted many of the theoretical optical considerations which are not essential to the routine use of the microscope. Some fifty of the more important detrital minerals are described and illustrated by drawings. The diagnostic features of each mineral are listed. Several methods for determining and plotting mineral frequencies from thin section and grain study are given and the application of statistical methods to determine the degree of correlation is explained. Various chemical methods which may be employed in the study of sediments are described and a chapter is devoted to the mass properties of sediments such as color, specific gravity, porosity, permeability, and plasticity. The final chapter outlines the laboratory equipment necessary for carrying on a petrographic analysis along the lines advocated in the book and some suggestions pertinent to the organization of the work are given.

The reviewer feels that the book could be greatly condensed, thereby reducing the price and increasing its usefulness as a manual. In its present form it is a reference book rather than a text. Too much space has been devoted to the theory and technique of mechanical and statistical analysis in proportion to the other technique which is necessary to make a well balanced study of a sediment.

The book is well written and illustrated, although the first part is somewhat technical. The references to the literature are very extensive and have been selected with considerable care.

This work is a valuable addition to the literature of sedimentary petrography and every student of the subject should be familiar with it.

STANLEY A. TYLER
University of Wisconsin

The examination of fragmental rocks, Revised Edition, by Frederick G. Tickell. x plus 154 pp., 54 figs., 20 tables. 7×10 inches. Cloth. Stanford University Press, Palo Alto, Calif., (1939). Price, $4.00.

This revised edition of Professor

Tickell's book has the same good qualities noted by a reviewer of the first edition; it "is clearly written, well illustrated, and substantially and attractively bound." Unfortunately, it also has most of the bad qualities, as the section on porosity and permeability (Chapter III) is the only one extensively revised. This chapter has been rewritten and increased to 24 pages, more than double its original length. Though the reviewer is not so familiar with the techniques of porosity and permeability determinations, this section appears to be an excellent and up-to-date treatment.

Chapter I is a page and a half introduction. Chapter II (23 pages) is titled "Size Analysis," but includes notes on "degree of rounding," representation of size distribution (mechanical analyses), and on thin section preparation. Very little change has been made in these chapters from the original edition. The method recommended for analysis of fine grained sediments is that of undisturbed settling in test tubes, one which was obsolete when the first edition appeared (1931). No mention is made of the hydrometer or pipette methods. "Degree of rounding" is determined by a modification of the Cox method, in which shape, not roundness, is determined. Wadell's extensive work on shape and roundness is not noted, nor are any of his papers included in the bibliography. The methods recommended for determining the skewness and kurtosis of frequency curves are different from those usually employed by students of sediments.

Chapter IV, "Preparation of Specimens" (13 pages), is also essentially unchanged from the first edition, with no reference to modern methods of disaggregation and dispersion, though considerable space is devoted to little-used means of mineral separation, such as electrostatic and dielectric methods.

No important changes are evident in Chapter V, "Identification of Minerals" (43 pages), or Chapter VI, "Description of Minerals Found in Sedimentary Rocks" (30 pages plus determinative tables). Chapter V attempts to present optical methods of identification and, according to the author, "does not presuppose a knowledge of optical mineralogy." In the reviewer's opinion it falls short of its objective, as the treatment is so brief that one unacquainted with crystallography and optics will find it confusing. There are also erroneous statements, as: "The latter [maximum extinction angle] will be given only when the grain is lying on a cleavage face parallel to the optic plane." This is stated as a general law, whereas it is applicable only to monoclinic minerals in which the optic normal coincides with crystallographic b. The description of minerals lists only one value for each index and one value for the birefringence, no allowance being made for variations in members of isomorphous groups. In fact, no mention of such variations is made. Optic orientation is not given in the descriptions, but is shown for 18 of the biaxial minerals in "orientation-cleavage diagrams" which should be very useful.

Many of the typographical and other errors which marred the first edition have been corrected, though a few new ones were made during revision. The bibliography has been increased from 105 to 137 titles.

The first edition of this book undoubtedly fulfilled a useful purpose in assembling a number of methods commonly used in the laboratory study of fragmental rocks. With the exception of the section on porosity and permeability, however, the revised edition ignores the great improvements made in laboratory methods in the eight years which have elapsed since the first edition appeared. Those not acquainted with the first edition will find some valuable suggestions in the book, but the reviewer feels that the disregard of modern techniques and other deficiencies limit its usefulness as a general laboratory manual.

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